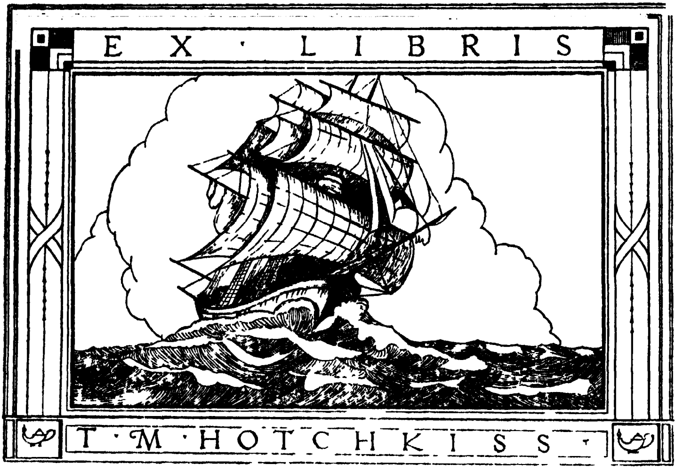
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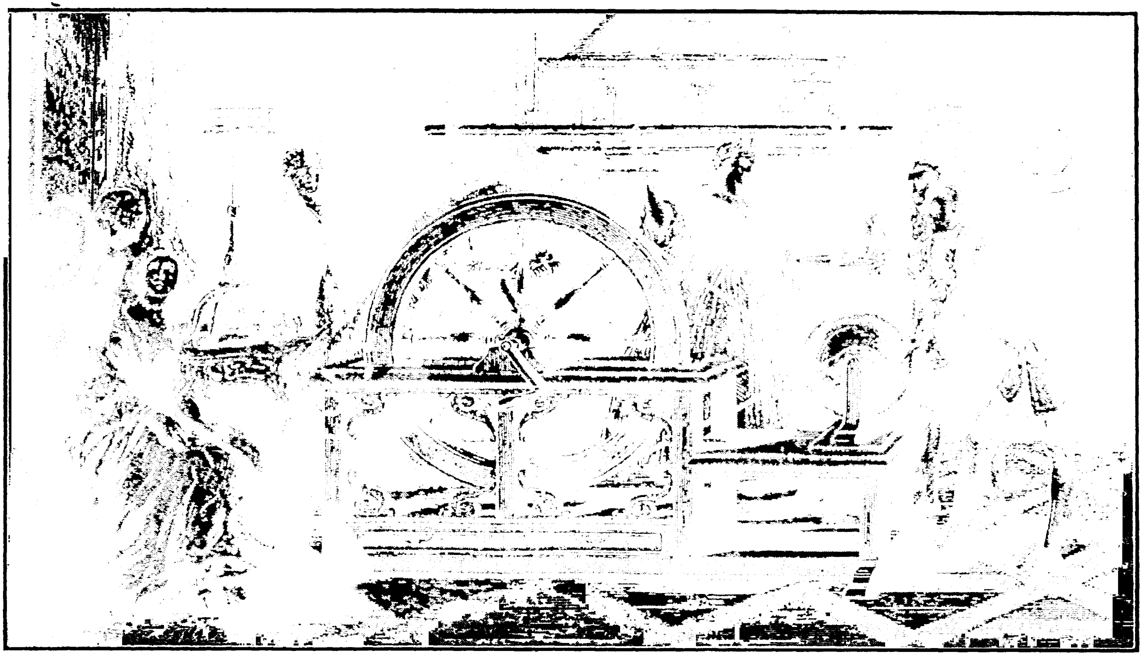
ELECTRICITY

What It Is and How It Acts



AN EARLY ELECTRICAL MACHINE—OTTO VON GUERICKE, 1650
A ball of sulphur was rotated, electricity being generated when it was rubbed with the hand

ELECTRICITY

What It Is and How It Acts

VOLUME I

BY

ANDREW W. KRAMER

Associate Editor Power Plant Engineering, Associate Member
American Institute of Electrical Engineers,
Institute of Radio Engineers

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PREFACE

AT A TIME when the scientific world is undergoing a house cleaning, when many of our most cherished ideas and theories are being upset by the new physics and when the theory of relativity and the quantum hypothesis are building for us a new strange universe, it may seem somewhat of a presumption to offer a book purporting to explain the nature of electricity. Perhaps it is. The title of the book, I admit, certainly is an audacious one and, mentally, I can picture the purists holding up their hands at the horror of it. Indeed, were it not for a sincere desire to dispel somewhat the unfortunate mental attitude which exists in regard to the nature of electricity and to indicate to those who are curious what is known about electricity, I, probably, would never have had the presumption to select it.

For electricity, ever since Thales first rubbed a piece of amber and found it endowed with a strange new power, always has been the mystery of mysteries. Somehow man has always been able to invent plausible explanations for nearly everything under the sun except electricity. Heat, light, sound, chemical action, even matter found ready interpretation in terms of other things but when an explanation of electricity was called for, our imaginative powers seemed to fail. "Nobody knows what electricity is" was the universal answer and thus it is today.

But is this view of electricity quite fair? True, there is much concerning electricity that is still unknown; the ultimate nature of the electron may never be known, but do we not know as much about electricity as we believe we know about other things?

Matter, for instance, is obvious. We all think we know what matter is; it is so universal that we feel it doesn't need explaining. Yet, the ultimate nature of matter is just as much a mystery as is that of electricity for the electron lies at the root of the mystery in each case. Similarly with heat; heat is generally accounted for on the basis of molecular impact and motion, but just how the energy of motion is converted into heat waves is quite as mysterious as the nature of the electron itself. Light, until quite recently was generally regarded as a wave phenomena in the ether notwithstanding the fact that it was humanly impossible to form a conception of the ether and today, thanks to Einstein and Planck we are not so certain that an ether exists or that light is even a wave motion. Yet, most people are perfectly satisfied with the explanation that light is a wave motion in the ether.

Since the electron seems to be the ultimate building block of the Universe and since all things must be explained in terms of the electron, there is no valid reason for attributing a more profound mystery to electricity than to other natural phenomena. Electricity consists of electrons in motion. That assertion is as perfectly definite and contains as much truth as the statement that matter consists of atoms in turn made up of electrons. If one is inadequate, so is the other.

Assuming the existence of the electron and attributing to it the properties and characteristics determined by years of experimental research, it is perfectly possible to construct a logical and highly satisfactory theory of electricity—one capable of accounting for nearly all known electrical phenomena and which is corroborated in every way by sound experimental evidence.

In this book I have endeavored to set forth in as simple as possible a manner, the role played by the electron in ordinary electrical phenomena with which we are all familiar. Starting with a description of the properties of the electron I have endeavored to show, step by step, the manner in which this universal entity is able to account for electrical and related phenomena. While an attempt has been made to adhere strictly to electrical phenomena, this, in a discussion of something so universal as the electron is not always possible. The digressions, however, are not numerous and in each case are necessary to a proper understanding of the subject.

The material contained in this volume was first published in serial form in Power Plant Engineering during 1928 and 1929. Its enthusiastic reception by many of the readers and the many requests for the articles in book form induced the publishers and myself to compile them into the present volume.

This book, it must be understood, is not an elementary study of electrical engineering. It is not concerned with the solution of practical electrical problems nor is any attempt made to deal with the constructional features of electrical equipment. It is a work rather which deals with the fundamental principles which underlie the laws upon which electrical engineering is based.

In this first volume there is discussed only those phenomena which are not concerned directly with the electromagnetic radiation of energy. Radiation phenomena, radio-activity, the electron theory of magnetism and related subjects will receive treatment in a second volume.

In the preparation of a work of this kind the material, naturally, is obtained from many sources. As far as possible I have endeavored to indicate the source in each instance not only for the purpose of giving credit to those to whom credit is due but also to enable the reader to pursue his studies further should he so desire.

In presenting this book I wish to express my appreciation to Arthur L. Rice, Editor of Power Plant Engineering, for his encouragement and the opportunity to make the book possible.

Chicago, 1929. A. W. K.

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CHAPTER I

INTRODUCTION

IT IS, PERHAPS, a natural human trait that those most intimately concerned with the everyday operation of electrical equipment should least concern themselves with speculations upon the fundamental concepts on which the art rests. In a busy world, with many interests competing for every one of the 24 hr. in a day, we are likely to take these things for granted and let matters go at that. A motor operates efficiently and does its work well—why worry about the reasons for its running?

This view of the matter, while it may be perfectly satisfactory to some, to the majority, in fact, is not conducive to the continuous advancement of the art and it is well that since the beginning of history there have always been curious individuals who were forever trying to find out just what "it was all about." Such a man was Thales of Miletus, who lived some 600 yr. B. C. and who first noticed that the rubbing of amber would induce in it a new and remarkable state now known as electrification.

This Thales was something more than a keen observer, however; he was also something of a philosopher and it is perhaps more than a mere coincidence that he, who first noticed the phenomenon of electrification, also first gave expression to the conviction that there must be some great unifying principle which links together all phenomena and is capable of making them rationally intelligible; that behind all the apparent variety and change of things there is some primordial element, out of which all things are made and the search for which must be the ultimate aim of all natural science.

Whether Thales ever suspected that the unifying principle he believed in lay in the curious phenomena he had discovered is not known; probably he didn't, but that he even thought about it is everlastingly to his credit. For it is because men like Thales and Democritus were curious and thought about the mysteries of nature that we, today, are able to enjoy the countless benefits which our knowledge of science has made possible. To those men we owe all that science has given us.

Today, we know that electricity—the same electricity that Thales wondered about—is itself the primordial element for which the old Greek scientist groped; that electricity probably is the only thing which exists in the universe and that the fundamental laws which govern the mechanism of the electron are capable of accounting for all physical, chemical and biological phenomena. The electron is the ultimate building block of matter, out of which all substances, every element that we know of, is built. In its essential ideas, however, our conception of the world as it exists in the mind of the modern physicist is perhaps little different from that held by the Greek philosophers 2000 yr. ago. The Greek philosophers of the school of Democritus (420 B. C.), Epicurus (370 B. C.) and Lucretius (Roman, 50 B. C.), held that the world is made up of atoms in incessant vibration. Today, we hold the same opinions, with this difference, however; the conception of the ancient Greeks had its roots in the realm of speculative philosophy while ours today is founded firmly upon scientific facts.

It is, of course, natural that in their quest for the unifying principle in nature men should have speculated upon the structure of matter first and electricity afterwards. Matter is obvious; universal—so much so, in fact, that it is taken for granted. We all think we know what matter is. We are so familiar with it in its various forms that we are inclined to think that it needs no explanation. Of electricity, on the other hand, we think we know less. Familiarity with electric phenomena comes into our lives much later than familiarity with matter, so that we feel electricity is a mystery compared to matter.

Similarly, our conception of energy has been very much less defined than that of matter. Energy was said to be a property of matter. A flywheel, revolving under its own inertia was said to possess energy. We could no more think of the energy existing without the flywheel than we thought electricity could exist without matter. Both of these views were held long after the establishment of the atomic structure of matter.

But as in the case of matter, which was shown to consist of atoms, first electricity was shown to have an atomic structure and now it seems that even energy itself is atomic. Furthermore, it appears that matter, the tangible stuff of which everything is made, is nothing more than a certain form of energy—that the two (matter and energy) are equivalent and that, just as there is an equivalent amount of mechanical energy for a certain amount of heat, so there is an equivalent amount of energy for a definite amount of matter. Just as 42,000,000 ergs of energy equal one calorie of heat, so one gram of matter may disappear as such, giving rise to (9×10^{20}) *900 million, million, million* ergs of energy.

In this concept of energy-matter, it may seem that electricity is left out of the picture, but this is not correct. In speaking of matter, we unconsciously think of matter in the aggregate, i.e., as we are aware of it through our senses, not as the physicist thinks of it, as a group of atoms, each built up of component electrical charges. The electron, the ultimate particle of electricity, therefore, is also the ultimate particle of matter.

Before we begin a detailed discussion of the electron and the part it plays in electrical phenomena, it will be interesting to trace briefly the historical facts surrounding the conception of the electron and what circumstances led to its discovery.

FIRST SUGGESTION OF THE ATOMIC NATURE OF ELECTRICITY

The first suggestion of the atomic character of the electric charge came from observation of the laws governing the passage of electricity through solutions. Before that it seems Franklin believed in the existence of an electrical particle or atom, but it is scarcely possible that he dreamed it would be possible, ever, to isolate and study by itself one of the ultimate particles of the "electrical fluid." The atomic theory of electricity was to him what the atomic theory of matter was to Democritus, a pure speculation.

In 1833, however, Michael Faraday, in experimenting with the passage of electricity through solutions, found that the passage of a given quantity of electricity through a solution containing a compound of hydrogen would always cause the appearance at the negative terminal of the same amount of hydrogen gas, irrespective of the kind of hydrogen compound which had been dissolved and irrespective also of the strength of the solution. A little thing in itself, yet how stupendous was its ultimate effect. For who, privileged to observe this young physicist in his laboratory, would have dared to predict that in the production of this bit of gas around an electrode lay a clue to one of the major mysteries in nature? Even Faraday, himself, could not have foretold that. Yet he pursued his researches. He found also that the quantity of electricity required to cause the appearance of one gram of hydrogen would always deposit, from a solution containing silver, exactly 107.1 grams of silver.

Now this was of extraordinary interest because the weight of the silver atom was known to be just exactly 107.1 times as heavy as the weight of the hydrogen atom and it meant that the hydrogen atom and the silver atom are associated in the solution with exactly the same quantity of electricity. Further experiments along this line soon made it clear that all atoms which are univalent in chemistry, that is, those which combine with one atom of hydrogen, carry precisely the same quantity of electricity; and all atoms which are bivalent, that is, those which combine with two atoms of hydrogen, carry twice this amount. In other words, it seemed as if the electricity could only be carried through the solution in certain definite blocks. These facts gave strong support to the atomic theory of electricity.

Striking as these discoveries were, they did not serve to establish the atomic nature of electricity. They were made at a time when attention began to be directed strongly away from the conception of electricity as a substance of any kind. Electricity had become to be thought of in terms of stresses or strains in the ether which surrounded the electrified body and from 1840 to about 1900 this conception was prevalent.

During this time the physicist was in a peculiar position, for when he was thinking of the passage of electricity through a solution, he thought of it in terms of specks or particles, each atom carrying an exact multiple of a unit electrical atom, while, when he was considering the passage of a current through a metallic conductor, he gave up the atomic idea and tried to picture a continuous fluid passing through the wire. He recognized two distinct types of electrical conduction, electrolytic conduction and metallic conduction. In the meantime, however, great advances were made in our knowledge of the behavior and effects of the electric current. The self-exciting dynamo was invented and absolute quantitative measurement laid the foundations of modern electrical engineering.

Notwithstanding the remarkable development in practical electrical engineering, at the beginning of the decade before 1900, physics and chemistry found itself in a somewhat lifeless state. True, there had been many refinements—new elements had been discovered, the electromagnetic theory of light had been enunciated by Maxwell and experimentally proved by Hertz; but in the main, there was a prevailing belief that all that was worth while had been done. Little more was known about the absolute nature of electricity than was known in Franklin's time. In the face of all attempts to learn something about it, it remained the baffling mystery it had always been.

Even at that time, however, there were in our college laboratories curious, twisted tubes of glass which, when excited by high voltage, would glow with beautiful iridescence. They were little more than curious playthings and of no earthly use. It was realized that something curious was going on inside these tubes but few realized that they contained the embryo of the most amazing discoveries of the next quarter of a century, and that they would raise the atomic theory of matter and electricity from a vague speculation with hardly a hope of experimental realization to a position of surety and fact. For it was in these Geissler tubes that the first discharges of electricity through gases were observed and where, for the first time electricity was observed *apart from matter.*

CROOKES' EXPERIMENTS

It was Sir Wm. Crookes, who, in examining such discharges in bulbs, exhausted to a high degree by a new air pump he had made, first observed the so-called cathode ray streaming away from the negative electrode.

Since there was very little air or gas in the tube, he came to the conclusion that this ray consisted of minute negatively charged particles projected across the bulb. He showed that they possessed the properties to be expected from such a stream for, on the one hand, they would heat bodies on which they fell, and on the other hand, they were deflected by a magnetic field.

These experiments at once opened up vast opportunities for research and discovery for here apparently was a fourth state of matter. The atomic theory of electricity, which had so long lain dormant, as it were, again came to the front. Of course, the proponents of the ether-strain hypothesis held that the cathode ray consisted of an electromagnetic wave of some sort, similar to light, but the experimental evidence was too strongly in favor of the negative-particle theory for the wave theory long to persist. Hertz showed that these rays could pass through thin sheets of metal and Lenard took advantage of this to coax them outside of the bulb and display their effects in the air outside.

Gradually the evidence for the atomic theory of electricity gained weight. True, the advocates of this theory had never relinquished it; in fact, in a paper read before the British Association at Belfast in 1874, G. Johnstone Stoney not only stated clearly the atomic theory of electricity, but actually went so far as to estimate the value of the unit electrical charge, i.e., the value of the smallest electric charge that is able to exist. Curiously enough, the value he obtained was about as reliable as any which had been found until within quite recent years. And it was this same Dr. Stoney who in 1891 first suggested the name "electron" for the natural unit of electricity.

Until the experiments of Crookes and for some time afterward, ideas as to how electricity is conducted through gases were vague. Some were inclined to attribute it all to dust particles. The real explanation of gas conduction was not found until after the discovery of X-ray in 1895. The convincing experiments were made by J. J. Thomson at the Cavendish Laboratory. The whole thing, in fact, grew obviously and simply out of the fact that X-rays and, a year or two later, radium rays, were found to render a gas conducting. The result was that gas conduction was shown to be due to charged particles, produced in the gas by X-rays, and that these charged particles, evidently of both plus and minus signs, disappeared by recombination when the X-rays were removed. Apparently the X-ray did something to the atoms of gas which made ''ions'' or ''travelers'' of them. The term ''ion'' was used first by Faraday in his explanation of conduction through liquids. So the conduction of electricity through gases was evidently electrolytic in nature.

Thomson's work in the ionization of gases by means of X-rays lent great impetus to the work of determining the ultimate electrical charge. Up to that time the only type of ionization that was known was that observed in solution and here the compound molecule such as sodium chloride (NaCl) always split up spontaneously into a positively charged sodium ion and a negatively charged chlorine ion. But in the ionization produced in gases by X-rays, something of an entirely different character took place, for it was observable in monatomic gases, that is, gases whose atoms do not combine with groups of two or more to form molecules. Plainly, the neutral atom of even such inert gases as nitrogen possessed minute electrical charges as constituents. In other words the atom, instead of being the ultimate indivisible unit we had thought it to be, was evidently a complex structure. *With this discovery, the atom as an ultimate, indivisible thing was gone, and the era of the study of the constituents of the atom began.*

By this time the conception of the electron, as simply a definite elementary quantity of electricity, had become quite definite, although little or nothing was known as to its mass, its charge or its relation to the atom as a whole. These questions at once began to interest the physicists and they began diligently to seek the answers.

THE DISCOVERY OF THE ELECTRON

Here J. J. Thomson's extraordinary insight into the problem began at once to bear fruit, and during the next few years there issued from the Cavendish Laboratory a wealth of most remarkable data. The first partial answer to the question regarding the mass of the electron came from a comparison of the relation of the charge to the mass of the hydrogen ion in solutions to that of the same relation in the negative ion in the gases of highly exhausted tubes. Thomson and Wiechert, independently, in 1897 showed that the relation of the charge to the mass for the negative ion in exhausted tubes was about 1800 times the value of the ratio between the charge and the mass for the hydrogen ion in solutions. Since the total quantity of electricity involved was about equal in gases and the solutions, the only possible conclusion to be drawn from this was that the negative ion appearing in electrical discharges in exhausted tubes had a mass only 1/1800 the mass of the hydrogen atom—the lightest of all atoms!

Next, they turned their attention to the positive ion. What was its mass? What was its relation to the negative ion? Although the researches on the positive ion were first carried out by Wien, the most successful work on this problem was done by Thomson. The result was that it was proved quite conclusively that the ratio of the charge to the mass of the positive ion in gases was never larger than it is for the hydrogen ion in electrolysis and that it varied with the different sorts of residual gases just as it is found to do in electrolysis.

With the results of these investigations on the mass of the ions available the physicist, in the few years before 1900, was able to form the first mental picture of the neutral atom and understood for the first time the process of ionization. The atom, it appeared, consisted of a positive ion of practically the same mass as the atom itself, with which was associated one or more negative ions each having only 1/1800 the mass of the lightest of all atoms—the hydrogen atom. Furthermore, the mass of the negative ion was always the same, regardless of how produced or in what gas. And the process of ionization appeared to be nothing more than the detachment from a neutral atom of one or more negative ions, or corpuscles as Thomson called them.

All of this happened before 1900. Since that time great advances have been made in our quantitative knowledge of the elements involved in the structure of the atom, but the conclusions reached in regard to the nature of electricity and its relation to matter have not been modified in their essentials.

With the existence of the electron fairly well established attempts to determine its charge and mass went forward rapidly. Numerous investigators attacked the problem, each succeeding measurement being made with increasing skill and understanding. They reached their high water mark in the brilliant oil drop experiments of Millikan at the University of Chicago. Millikan observed the behavior of a single drop of oil floating in dust free air between electrically charged plates. As the droplet became charged by attaching to itself or losing an electron, its electric charge increased or decreased and it was drawn to one or the other of the plates. By carefully noting the charge applied to the plates by a high voltage battery, and measuring the speed of the droplet under various conditions, Millikan was able to calculate with great accuracy the amount of charge due to a single electron.

These experiments of Millikan are of tremendous interest and will be described in greater detail in later chapters. It will be helpful toward a better understanding of the experiment to first learn something of the part played by the electron in ordinary electrical phenomena. This will be discussed in the succeeding chapters.

CHAPTER II

FUNDAMENTAL CONCEPTIONS

IN THE PRECEDING chapter, we traced briefly the history of the electron theory of electricity and described the principal events which led to the discovery of the electron by its behavior in the vacuum tube. We now come to a more detailed consideration of the electron itself and its relation to ordinary electric phenomena with which we are familiar.

Everybody is more or less familiar with simple experiments having to do with electrically charged bodies. Since the time of Thales it has been known that amber when rubbed with fur or silk will attract small bits of paper. Sheets of paper if rubbed on a dry winter day will crackle and when pulled apart will give off minute sparks. Sometimes, it is only necessary to walk across the carpets in our homes, to enable us to draw sparks from radiators and other grounded objects.

What is the explanation of these strange phenomena? How does a body become charged and why? Wherein does a charged body differ from one that is not charged?

The answers to all of these questions are to be found in the modern conception of matter—in the fact that every atom of matter is made up of minute electric charges—tiny particles of positive and negative electricity, in fact. What we know of these particles of electricity has been obtained almost entirely from the action of the negative particle, commonly known as the electron. Originally, the term electron was used merely to denote the unit electric charge without regard to whether its sign was negative or positive but in late years the electron has come to mean only the negative charge. For the positive electron the word proton has been coined.

PROPERTIES OF THE ELECTRON

All electrons are similar, regardless of the kind of atoms from which they are obtained. Thus an electron from the hydrogen atom acts precisely the same as the electrons from atoms of helium, iron, gold or oxygen. It is definite in amount, always being exactly the same, and so far as we know cannot be divided into smaller parts.

Electrons, all being alike and having charges of the same sign, tend to repel each other with relatively enormous forces. Two electrons placed at a distance of 1 cm. (3/8 in.) from each other in a vacuum will repel each other with a force of 1.16×10^{-19} dynes. This, of course, is an exceedingly small force but it is tremendous when considered relative to the size and weight of the electron. It has been estimated[1] that if it were possible to collect 2 grams of pure electrons and to form them into two equal spheres each weighing one gram and if these spheres were held 1 cm. apart as shown in Fig. 1, they would repel each other with a force of 320 million million, million, million tons!

To form a conception of an electron in terms of anything with which we are familiar, is practically impossible. Its mass, in technical language, is 8.8×10^{-28} grams and its electric charge 1.59×10^{-19} coulombs. This, of course, means nothing to the ordinary mind familiar only with such units as the watt, the ampere and other practical quantities, and it is only when such practical units as amperes are expressed in terms of electrons that we can begin to form some idea of their astonishing smallness. Consider, for example, the quantity of electricity that flows through an ordinary 16 candle power carbon filament electric lamp in one second, worth about 1/100,000 of a cent at ordinary rates.[2]

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[1] Fournier, "The Electron Theory."
[2] R. A. Millikan, "The Electron."

If the three million inhabitants of a city like Chicago should begin to count the electrons passing through such a lamp in one second, and were to keep on counting them out at the rate of two a second, and if no one of them ever stopped to eat, sleep or die, it would take them just about 16,700 yr. to finish the task.

In attempting to form a mental picture of the electron, however, it is best not to associate in mind the idea of a small particle having definite size and mass in the ordinary sense, because the size and mass of an electron are things about which we must speak somewhat reservedly. The electron makes itself known only by virtue of the electric and magnetic field created by its presence and the thing that we call mass in an elec-

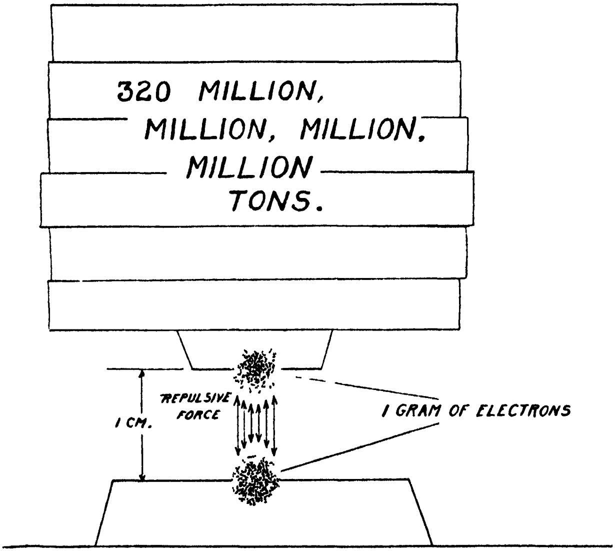

FIG. 1. IF IT WERE POSSIBLE TO COLLECT 2 GROUPS OF PURE ELECTRONS AND DIVIDE THEM INTO TWO GROUPS 1 CM. APART, THEY WOULD REPEL EACH OTHER WITH FORCE OF 320,000,000,000,000,000,000,000,000 TONS!

tron may be merely a form of electromagnetic energy. For the present, however, and for purposes of explanation, we shall continue to speak of them as definite particles, regardless of what their absolute nature may be.

From the electron point of view, a negatively charged body is one having more than its normal number of electrons, and a positively charged body is one having less than its normal number. A normal atom is not charged, because the number of positive electric charges in such an atom is exactly balanced by the number of negative charges. Such an atom exerts no attractive or repulsive force upon other atoms.

THE STRUCTURE OF THE ATOM

In the light of modern research, a neutral atom consists of a positively charged center, called the nucleus, around which are grouped a number of electrons, the combined negative charge of which is just sufficient to neutralize the excess positive charge of the nucleus. The nucleus itself consists of closely grouped numbers of positive electrons and negative electrons, but there are always more positive electrons or protons, than negative electrons. It is this excess of protons over electrons that gives the nucleus its positive charge.

The electrons which are external to the nucleus are separated from it and from each other by relatively large distances, despite their smallness. Perhaps as good a picture of an atom as may easily be formed is obtained by a comparison with our solar system. The distances between the sun and planets are very large compared to the diameters of any of the planets or even the sun itself. If we now imagine the sun to be extremely small as compared to the size of the earth and then imagine all the distances and sizes to be reduced proportionately, until the system is invisible with even the most powerful microscope, we have a possible picture of a simple atom. In this comparison, it is necessary to make the sun smaller than the earth because the nucleus is small compared to the electron. Offhand, this may sound absurd because we have said already that the nucleus is composed of numbers of positive and negative electrons, but experience seems to indicate that the union of two or more protons with one or more electrons is a smaller particle than is a single isolated electron. It seems that in the nucleus, the electrons and protons may merge in a union so close that their combined size is less than the electron alone! This in itself seems to demonstrate the absurdity of attributing any such quality as size to an electron. The size of an electron probably is not a constant but varies with its location.

The simplest atom is that of hydrogen. This consists of only one proton and one electron. The two elements are probably whirling about each other in space much like a rapidly whirling dumbbell except that there is no rigid connection between them. The diameter of this atom is about two hundredths of a millionth of a centimeter but this is about one hundred times as large as the diameter of the electron.

The nucleus itself is less than one three millionth the size of the electron, in fact, the nucleus of the hydrogen atom is a sphere so small that, if it were magnified to the size of a pin's head, that pin head would, on the same scale of magnification, become magnified to the radius of the earth's orbit around the sun, a sphere some 185,000,000 mi. in diameter.

Other atoms are built up in the same way, except that they are more complicated because of the greater number of external electrons. In fact, it is the number and arrangement of these outer electrons that determines what the atom is, whether it is hydrogen, or

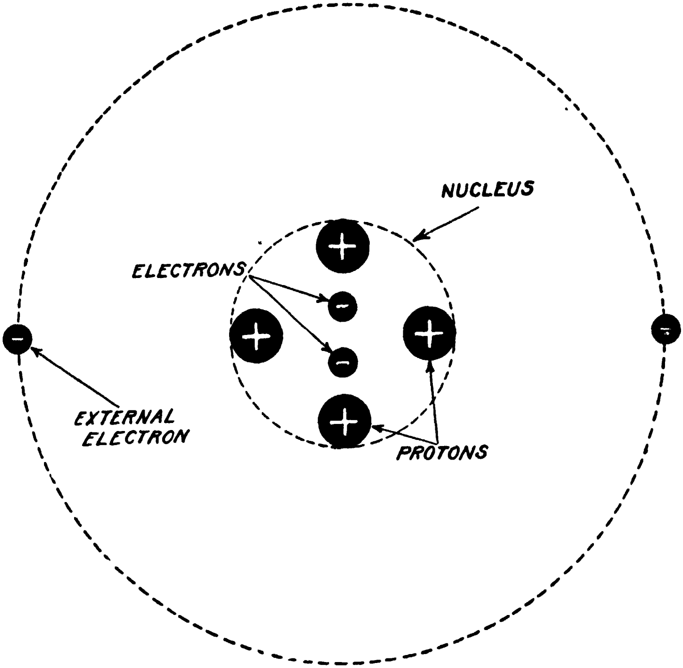

FIG. 2. CONVENTIONAL MODEL OF THE NEUTRAL HELIUM ATOM

NOTE: In considering this diagram, one must keep in mind the fact that in the actual atom the nucleus would be very much smaller than either of the two external electrons. This may sound absurd, but experiments seem to indicate that this is so. Evidently, when two or more protons combine with one or more electrons to form the nucleus, the attractive forces are so great that the total mass of the group is squeezed into a space smaller than any of the component elements.

copper or radium, etc. In other words, all substances, are made up of the two elementary quantities, positive and negative electrons, and the difference between substances is due only to the difference in the number and arrangement of electrons in the atom.

Next in simplicity to the hydrogen atom is the atom of helium. This consists of a nucleus and *two* external

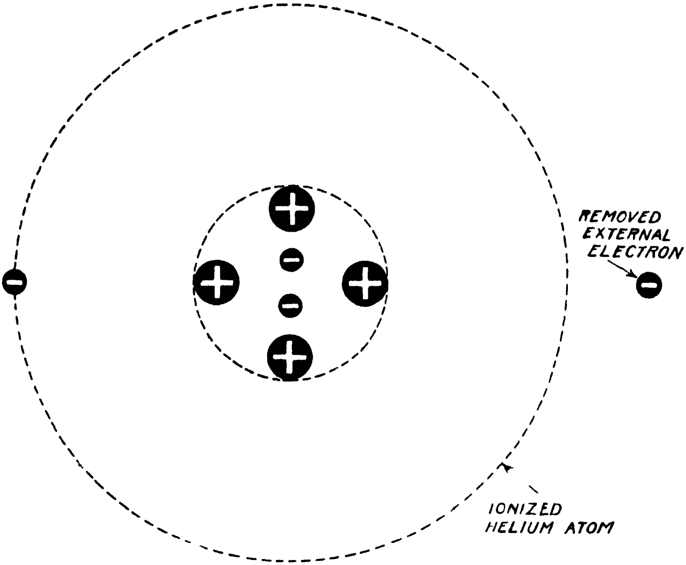

FIG. 3. CONVENTIONAL MODEL OF AN IONIZED HELIUM ATOM

NOTE: This, it will be obvious, is the same arrangement shown in Fig. 2 except that one external electron has been removed, leaving the atom as a whole with an excess of positive charge.

electrons. The nucleus contains four protons (positive electrons) and two electrons, thus providing the excess of two protons to account for the two external electrons. A conventional model of a neutral helium atom is shown in Fig. 2.

Atoms of other substances have a more complicated nucleus and a larger number of outer electrons. The atom of sodium, for instance, has 11 outer electrons, that of sulphur 16 and of oxygen 8. Uranium, the heaviest of all elements, has 92 external electrons. There are exactly 92 chemical elements, all of which may be arranged in a series with hydrogen at one end and uranium at the other, so that each one will differ from the two on each side of it by the same amount of electrical charge on the nucleus and by one external electron.

The orbits of the outer electrons draw closer to the nucleus as the latter becomes heavier, but they always remain at the same distance for the same substances.

With this conception of the atom, it will be obvious that the atom, instead of being solid matter, as was once thought, is in reality mostly space. The electrons composing the atom may be compared to a few grains of sand in a large cathedral, the cathedral representing the outer boundary of the atom. The electrons fill the dimensions not because of their bulk but rather because of their energy. Oliver Lodge once said that electrons occupy the otherwise empty region of space which we call the atom in the same sense that a few scattered but armed soldiers can occupy a territory—occupying it by forceful activity, not by bodily bulk.

Having presented a picture of a simple normal (neutral) atom, we are now in a position to discuss what happens when a body is electrically charged. Suppose that by some means or other the balance between the negative and positive charges in an atom such as is shown in Fig. 2 is destroyed—suppose we remove one of the external electrons as shown in Fig. 3. The atom is now unsatisfied, so far as the balance between positive and negative charges is concerned. The excess of one proton in the nucleus gives the atom a positive charge. In this state the atom is said to be ionized.

If the removed electron (or any electron) is permitted to return to the atom, the balance of charge is restored and the atom is once more neutral.

It is evident from this that a positively charged body is one which has been deprived of some of its normal number of electrons. In the same manner, a negatively charged body is one in which the atoms have acquired more than their normal number of electrons. When a piece of sealing wax is rubbed with dry flannel, the wax becomes negatively charged and the flannel positively charged. Evidently, in the act of rubbing, the friction between the flannel and the wax must have rubbed some of the electrons off the atoms composing the flannel and left them on the surface of the wax.

Since the surface atoms or molecules (a molecule is a group of atoms) of the flannel are now deficient in electrons and the surface atoms or molecules of the wax have an excess, if the wax and the flannel are left together after being rubbed, there will be a readjustment of electrons, the excess of the wax returning to the deficient atoms of the flannel.

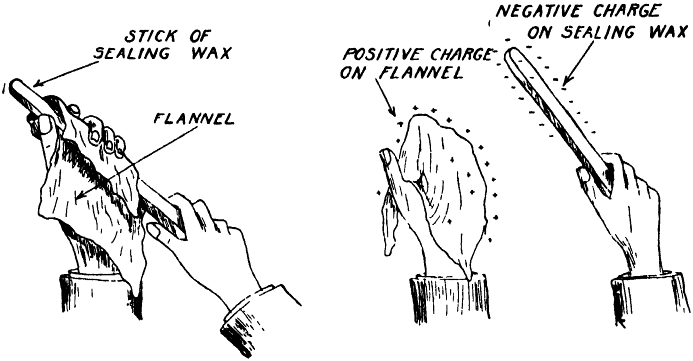

FIG. 4. WHEN A STICK OF SEALING WAX IS RUBBED WITH FLANNEL, THE WAX ACQUIRES A NEGATIVE CHARGE AND THE FLANNEL A POSITIVE CHARGE

So it is seen that the phenomenon of electrically charging and discharging bodies is fundamentally very simple. To understand it, it is merely necessary to have a simple conception of the structure of an atom, and to know that a neutral atom must always have just as many positive charges as it has negative charges.

With this much understood we are now prepared to take up in greater detail the actual structure of more complex atoms. Electrical phenomena are closely related to the atomic structure of matter, and a knowledge of the latter is essential to a proper understanding of the former.

CHAPTER III

ARRANGEMENT OF ELECTRONS IN ATOMS

TO THOSE WHO HAVE read the preceding chapters in anticipation of learning something about electricity, it may seem that we are unduly slow in getting started and that we have been sidetracked onto a discussion of the atom. This is necessary, however. The atom plays a vital part in most ordinary electrical phenomena and a knowledge of the former is essential towards an understanding of the latter.

An atom, we have learned, is a complex structure resembling a miniature solar system, consisting of a central positively charged nucleus, with one or more electrons grouped around it, the total negative charge of all the electrons being just sufficient exactly to neutralize the excess positive charge of the nucleus. An electrically charged body is one in which a number of atoms have lost or gained electrons below or above the number required to satisfy the normal (uncharged) system. The amount of electric charge carried by a body depends entirely upon the number[1] of atoms in that body so affected. If but few of the atoms of a body have had an electron removed (or added) the body has a small charge; if a large proportion of the total number of atoms in the body have had an electron removed (or added) the body is highly charged.

CONSIDERATIONS UNDERLYING CONCEPTS OF THE ATOM

In discussing the structure of the atom, it is necessary to preserve a logical attitude of mind, for after all, in trying to form a mental picture of the atom we are engaging in a process in which reason plays an important part. We must consider the fact that all we know about the atom is learned not by actual observation but by certain logical deductions based upon the physical, chemical and electrical effects of the atom under certain conditions. As a matter of fact, we can not say definitely that we know just how the component elements of the atom are arranged but it is logical to suppose (and there is much experimental evidence for this view)

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[1] Always a small proportion of the total number of atoms constituting the body.

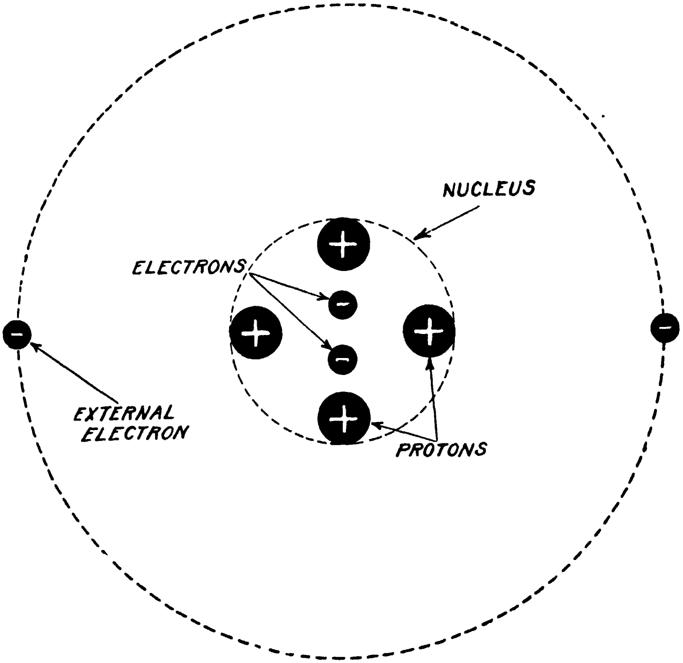

FIG. 5. CONVENTIONAL MODEL OF THE NEUTRAL HELIUM ATOM

Note: In accepting the Bohr conception of the atom, it is necessary to differentiate between two kinds of electrons: first, those which revolve externally with respect to the central nucleus and in orbits comparable with the diameter of the atom itself, and a second group which are intimately associated with the nucleus.

that electrons revolve around the positive center or nucleus in much the same way as the earth and planets revolve around the sun. For positive and negative charges attract and it is only by assuming the electrons to possess a centrifugal force due to rotation that it is possible to explain how they can maintain themselves in opposition to the attraction of the nucleus. This conception of the atom, together with certain mathematical deductions supporting experimental evidence, was first proposed by Professor Niels Bohr and this conception is usually referred to as the Bohr atom.

Of a number of theories advanced, the Bohr theory has been the most satisfactory in accounting for radiation and electrical phenomena. True, other theories have been proposed which have their merits so the question of just how the atom is constructed is not entirely settled. It is well, therefore, in accepting the Bohr atom, to do so with an open mind. All through the ages, it has been man's failing to interpret unknown phenomena in terms of that with which he was already familiar. This is but natural but in the scientist it should be constantly guarded against, for it often leads to erroneous conclusions. It is, of course, illogical to suppose that a law which holds true in a certain range ot space and time will not hold true in a different range of space and time, for that would be accusing Nature of an inconsistency that she does not deserve.

At the same time, it is logical to suppose that a law which gives certain results in one space and time will give entirely different results in another space and time, because of certain unknown modifying influences. The trouble is not with nature's laws but with our ignorance of modifying influences. There is no inconsistency in Nature.

Scientific knowledge accumulates gradually by a combination process of reasoning and experimental research.

A certain theory or conception may serve its purpose for years, when suddenly new experimental evidence upsets it completely but this does not necessarily imply that the original hypothesis was entirely false, or in the exceptional case that it was false, that it had not served some useful purpose. The spurious theory may have furnished the idea for the experiment which finally resulted in its overthrow. In scientific research the scientist and the philosopher are interdependent.

So in presenting the Bohr atom, while we caution the reader against a too rigid belief in the actual arrangement it supposes, at the same time we cannot overemphasize its importance in furnishing us with the vast amount of practical scientific knowledge forming the basis of modern physics. For the Bohr theory reveals the finer and more subtle details of the structure of the atom and serves to unify and explain a vast amount of unrelated physical, chemical and electrical phenomena.

In accepting the Bohr view of the atom, it is necessary first to differentiate between the two groups of electrons within the atom, first those which revolve externally with respect to the central nucleus and in orbits comparable with the diameter of the atom itself, and a second group, which are intimately associated with the nucleus and which, if they revolve at all, do so in orbits closely associated with the positive charge. Thus we have the atom shown in Fig. 5.

In our explanation of the nature of an electric charge, we have seen that the removal (or addition) of an external electron from an atom does not fundamentally alter the nature of that atom. An atom of copper with an external electron removed is still an atom of copper. The fact that rubbing sealing wax with flannel removes electrons from the atoms in the wax does not necessarily alter the wax. It is still wax. So we know that it is not merely the number of external electrons that differentiate one atom from another.

DIFFERENCE IN VARIOUS MATERIALS DUE TO CHARGE ON THE NUCLEUS

The secret of the difference between atoms of different materials, copper, iron, oxygen, etc., therefore, must lie in the nucleus and experiments have clearly proved this. The man who did most towards solving this important problem was a scientist by the name of Moseley. Few people probably have ever heard of Mosely—yet to this brilliant young Oxford graduate, only 27 yr. old when his promising career was cut short at Gallipoli during the war, must go the credit for conducting one of the most profound and brilliant feats of scientific research of modern times. For when Mosely, in 1912, turned the X-ray on matter—literally and figuratively—and made it disclose the skeleton of the atom just as certainly as it reveals the position of the bones in the human body, we were able for the first time to understand the reason for the difference between gold and iron and lead and other elements.

Space will not permit us to describe Mosely's experiments here, further than to say that by stimulating the electrons in atoms of different substances by X-rays he was able to cause these electrons themselves to emit X-rays whose properties he examined. From these X-ray spectra, he found that the net charges on the nuclei of the atoms were proportional to the numbers which would be obtained by arranging all the atoms (that is, of all the chemical elements) in a row in the order of their atomic weights, and then numbering them according to the position they occupied in the row, starting with hydrogen, the lightest.

In other words, if we call the charge on the nucleus of the hydrogen atom, e, that on the next heavier element, helium, would be 2e, that on the next heavier 3e, and so on. The entire 92 elements can be grouped in this fashion. The number which designates the charge on the nucleus in terms of the charge of the nucleus of the hydrogen atom is called the *atomic number* of that element and the nucleus of the hydrogen atom itself is the proton we have been discussing.[2] In the accompanying table is presented a list of the eleven lightest elements arranged in the order of their atomic weights, and showing the simple relation between the charge on the nucleus and the position they occupy in the column.

A LIST OF THE ELEVEN LIGHTEST ELEMENTS ARRANGED IN THE ORDER OF THEIR ATOMIC WEIGHTS

Atomic Weight	Element	Symbol	Charge on Nucleus (Atomic No.)
1.008	Hydrogen	H	e
4.	Helium	He	2e
6.94	Lithium	Li	3e
9.1	Beryllium	Be	4e
11.	Boron	B	5e
12.	Carbon	C	6e
14.01	Nitrogen	N	7e
16.	Oxygen	O	8e
19.	Fluorine	Fl	9e
20.2	Neon	Ne	10e
23.	Sodium	Na	11e

ATOMIC NUMBER AND ATOMIC WEIGHT MUST NOT BE CONFUSED

These two terms, atomic weight and atomic number, must not be confused. If we add one proton to the nucleus, we increase the atomic number by unity. If, however, we add a proton and an electron together, we do not change the charge on the nucleus at all. Its atomic number is the same as before and the external electrons travelling around it are quite unaware of the change. The weight of the atom will, however, be changed. It is possible, therefore, to have atoms with the same atomic numbers but with different atomic weights. Such atoms are called isotopes. In other words, isotopic elements are those which are not separable, therefore not distinguishable by any known chemical methods but which may be differentiated by differences in their physical properties.

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[2] W. F. G. Swan, "Journal of the Franklin Institute."

Since the atomic number is a measure of the net charge on the nucleus, it is evident that it is also a measure of the number of external electrons in the neutral atom. In other words, the atomic number tells us at once how many external electrons the neutral atom requires. These external electrons are exceedingly important, for it is in them, in their number and arrangement, that we find the explanation of chemical combination. The external electrons are also responsible for the production of light and X-rays.

CHEMICAL COMBINATION

In chemistry, the ability of one element to combine with another is called valance. Some elements combine readily with others, some not at all. Elements which do not combine with others are said to be inert, examples being helium, argon and neon.

Whether an element combines readily with another depends upon the external grouping of the electrons in the atom. In his exceedingly interesting book, "Within the Atom,"[3] John Mills draws an interesting parallel between the arrangement of the nucleus and electrons in atoms and a group of children playing a circle game about a teacher. "Suppose that the game goes best with eight in the ring but is possible with any number between 6 and 10. If 10 are playing, that is, if the teacher's responsibility is for 10, as might be the case for electrons if the nucleus has ten excess protons, then there is some crowding. An opportunity for two children to join an adjacent but less crowded circle will be welcomed by the children, and by the teacher also, if she can satisfy her quantitative obligations by supervising their play in a neighboring circle."

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[3] D. Van Nostrand Co., N. Y.

In the same way, an atom with a circle crowded by electrons is in an unsatisfied condition which is favorable to losing electrons. If it does so, it will have more protons than electrons and an atom with this tendency towards an excess of protons is said to be electropositive. Such an atom can supply atoms to any other atom which can accommodate them in its circle but if it does so, the two atoms must remain together, for each nucleus has responsibility for a definite number of the total electrons. In this way, a molecule of two atoms is formed. Of course, in order that the second kind of atom may accommodate the excess of the former, it is necessary that it have a complementary need. In other words, it must have fewer electrons than can be satisfactorily accommodated in its ring. Such an atom is said to be electronegative.

On the other hand, if an atomic system has a number of electrons just sufficient to be satisfactorily accommodated in its circle game, it will have no tendency to part with nor acquire electrons belonging to other systems and such atoms are said to be inert. Atoms with more electrons in their rings than can comfortably be accommodated in this circle game are electropositive.

CHAPTER IV

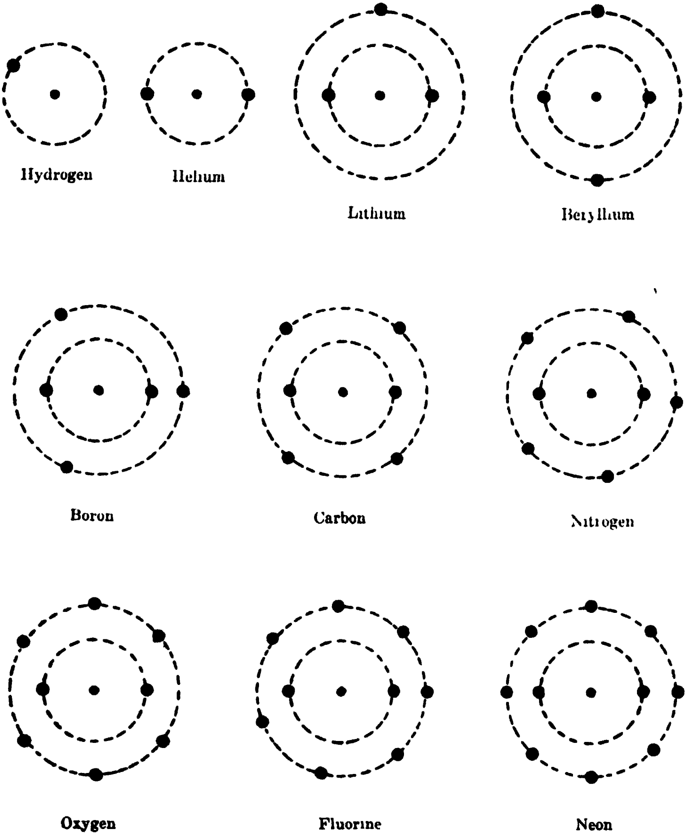
STRUCTURE OF ATOMS OF VARIOUS ELEMENTS

HAVING LEARNED something about the general structure of the atom and the principles underlying the process of chemical combination, we will now consider in some detail the actual arrangement of electrons in the atoms of the various chemical elements.

The hydrogen atom, we have seen, has only one electron revolving around its nucleus, while the helium atom has two. These two electrons are probably disposed on diametrically opposite sides of the circle, forming a stable arrangement, which probably accounts for the inertness of this element. It is perfectly satisfied and there is no tendency to acquire or lose electrons.

With three electrons in an atom, a different arrangement obtains. The ring holding the two electrons of the helium atom is stable and cannot accommodate any additional electrons, so when the excess positive charge on the nucleus is such that the atom requires three external electrons, the third is disposed in an orbit by itself which is just twice as far from the nucleus as the inner ring and capable, therefore, of accommodating four times as many electrons. Thus, this next orbit requires 8 electrons to form a perfectly stable system and the atom which satisfies this requirement is that of a gas called neon. This is the gas which is being used in those red orange electric sign lamps so common at the present time. The atom of neon has ten electrons, two in the inner ring and 8 in the outer. See Fig. 6.

Between the two stable atoms, helium and neon, there are seven atoms (see table), each differing by an external electron, which have a tendency to acquire or lose electrons depending upon whether the systems are



Hydrogen Helium Lithium Beryllium

Boron Carbon Nitrogen

Oxygen Fluorine Neon

FIG. 6 A SIMPLE REPRESENTATION OF THE TEN LIGHTEST ATOMS

closer to the helium or neon atoms in the table. It is easier for lithium, which has only one electron in the second orbit, to lose an electron, producing the stable arrangement of the helium atom, than it is to acquire 7 electrons, to give it the 8 required. Similarly, in the case of beryllium, which has 4 electrons in the second ring, it it easier to lose 2 than to acquire 6. The same is true of boron, which prefers to part with 3 rather than to acquire 5. Thus, because they would rather give up electrons than acquire them, all of

PARTIAL LIST OF THE CHEMICAL ELEMENTS ARRANGED IN THE ORDER OF THEIR ATOMIC NUMBERS

1.	Hydrogen	H
2.	Helium*	He
3.	Lithium	Li
4.	Beryllium	Be
5.	Boron	B
6.	Carbon	C
7.	Nitrogen	N
8.	Oxygen	O
9.	Fluorine	Fl
10.	Neon*	Ne
11.	Sodium	Na
12.	Magnesium	Mg
13.	Aluminum	Al
14.	Silicon	Si
15.	Phosphorus	P
16.	Sulphur	S
17.	Chlorine	Cl
18.	Argon*	A
19.	Potassium	K
20.	Calcium	Ca
21.	Scandium	Sc
22.	Titanium	Ti
23.	Vanadium	V
24.	Chromium	Cr
25.	Manganese	Mn
26.	Iron	Fe
27.	Cobalt	Co
28.	Nickel	Ni
29.	Copper	Cu
30.	Zinc	Zn
31.	Gallium	Ga
32.	Germanium	Ge
33.	Arsenic	As
34.	Selenium	Se
35.	Bromine	Br
36.	Krypton*	Kr
37.	Rubidium	Rb
38.	Strontium	Sr
39.	Yttrium	Y
40.	Zirconium	Zr
41.	Niobium	Nb
42.	Molybdenum	Mo
43.		
44.	Ruthenium	Ru
45.	Rhodium	Rh
46.	Palladium	Pd
47.	Silver	Ag
48.	Cadmium	Cd
49.	Indium	In
50.	Tin	Sn
51.	Antimony	Sb
52.	Tellurium	Te
53.	Iodine	I
54.	Xenon*	X

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*Transition systems.

these elements, lithium, beryllium and boron, are said to be electro-positive.

According to the same line of reasoning, nitrogen, oxygen and fluorine, which have respectively 5, 6 and 7 electrons in the outer ring or shell, are electro-negative. It is easier for these atoms to acquire electrons to give them the number required for stability than to lose them. Fluorine tends to acquire one electron and is said to have a negative valence of one and a positive valence of seven.

We have now accounted for all the atoms between helium and neon except one, namely the all-important element, carbon, with four external electrons in the outer ring. This system is midway between the helium and neon atoms and its positive and negative valences are equal. It has four electrons in its second shell and since they repel each other, probably assume positions such as form the corners of a solid figure of four equal sides. A system of this kind, which will as readily part with electrons as acquire them, should combine readily with other atoms and this happens to be the case. Carbon enters into all organic compounds.

Proceeding now to one atom with eleven electrons, we again find that the extra electron (over the number giving the stable system of neon) must find its place in a third orbit or outer shell. This third shell is practically coincident with the second and is capable of accommodating the same number of electrons, namely eight. The first element having this third shell is sodium, consisting of a nucleus with an excess positive charge of eleven, an inner shell with two electrons, a second shell twice as far from the nucleus as the first shell with 8 electrons and a third outer shell with one electron. Sodium, therefore, is in much the same condition as lithium, that is, it has a tendency to lose the outermost electron to give it the stability of the neon atom. Like the lithium atom, it has an electro-positive valence of one, and an electro-negative valence of seven. The next element (table), magnesium, has two electrons in the third shell and, like beryllium, has an electro-positive valence of two and an electro-negative valence of six.

So we proceed, adding an electron in the outer ring, until we come to argon, with 8 electrons in the third shell. This system, like that of neon, is stable and there is no tendency for this atom to acquire or lose electrons. Midway between neon and argon is the element silicon, which has the atmospheric properties of carbon. It has 4 electrons in the third shell and will as readily part with them as acquire 4 additional electrons.

From what has thus far been said, it must be obvious that in progressing from the simple hydrogen atom through those more complex structures, there is a periodic recurrence of systems with similar properties. At certain points, stable or satisfied systems are reached, which are transition systems between those of positive and negative valence. These are the inert gases, helium, neon and argon, etc.

So far, we have accounted for 18 of the 92 different elements. The others are built up in a similar manner by the addition of other external shells. The outer shells differ from those already described in that they have capacity for a larger number of electrons. The fourth shell, for instance, which is presumably three times as far from the nucleus as the first, hence its area is nine times as great and its capacity for electrons is 18 instead of two.

As we proceed to atoms of high atomic number, the principles involved in their structure are the same but the actual arrangement is more complex. John Mills in his book, "Within the Atom", explains the structure of

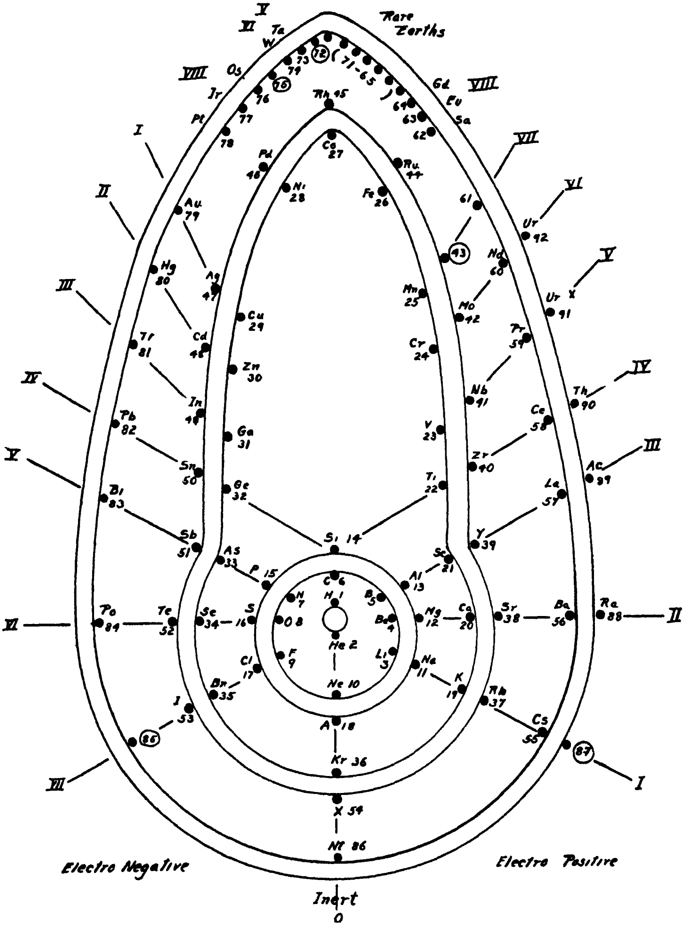

FIG. 7. ATOMIC SYSTEMS AT THE PERIODIC TABLE. PLACE NUMBERS CORRESPOND TO ATOMIC NUMBERS. SYSTEMS SIMILARLY SITUATED, AS INDICATED BY RADIAL LINES, HAVE SIMILAR CHEMICAL PROPERTIES. FROM JOHN MILLS' "WITHIN THE ATOM"

the atoms of the various atoms in an interesting manner by means of an ingenious diagram. This is a picture of the series of atomic structures as if there were a group of tables to be filled in by guests. These tables are roughly concentric as shown in Fig. 7. In Mr. Mills' own words, "one by one the atomic systems are seated and the order of their seating is given by the atomic numbers attached to their places. The first table seats only two; the next table, eight on each side; the third table, seating 18 on each side, must place some atomic systems in positions which do not correspond with any of those at the second table. There is, however, a correspondence between atomic systems which are opposite to one another at the same table. The fourth table differs in some ways from any of the inner ones and on one side it is only partially filled."

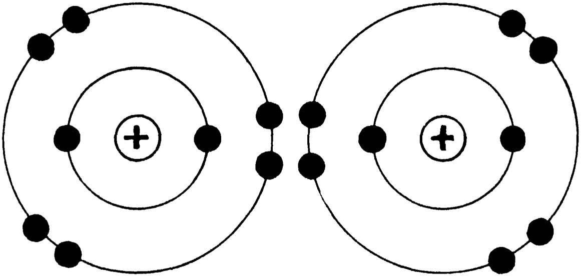

FIG. 8. THE OXYGEN MOLECULE

In representing the atomic systems in this manner, those elements which have similar characteristics lie on the same radial line. The radial line on which the stable or inert systems lie is marked zero. The others are marked with Roman numerals for the convenience of those who wish to compare this diagram with the usual tabular presentation of the periodic series of the chemical elements. The elements grouped on the right side of the plan are electro-positive while those on the left are electro-negative.

This arrangement, then, not only accounts for all of the 92 elements but gives us the reason for some of their properties. It tells us, for instance, that sodium (Na) combines with chlorine (Cl) to form sodium chloride (NaCl) which is our common table salt. By referring to the diagram, it will be seen that sodium with an atomic number of 11 has a positive valence of 1, while chlorine with an atomic number of 17 has a negative valence of 1. One is willing to give up an electron while the other has a tendency to acquire one. Hence the two systems combine to satisfy their respective desires.

In a similar manner, atoms of the same element combine. Oxygen with 8 electrons, for instance, lacks two to satisfy the requirements of its outer ring. Two atoms of oxygen, therefore, will combine into the molecule shown in Fig. 8. In this case, four electrons are shared by two atoms. Of course, in this case there are not enough electrons to ''go round'' but by remaining close together, each atom is in a manner responsible for two electrons in the adjacent system. While the two valency shells do not contain the sum of 16 electrons, each atom in effect has 8 in its valency shell. This is the reason why, in nature, oxygen is always found combined in molecules of two atoms each.

We have considered the arrangement of electrons within the atom in considerable detail because these electrons play an important part in electrical phenomena of all kinds. All electrical properties of conductors, solid, liquid and gaseous, are explained in terms of these electrons.

CHAPTER V

MATTER IN THE AGGREGATE

SOME TIME AGO, Dr. Whitney, director of the General Electric Research Laboratory, delivered a lecture before one of the scientific societies entitled "The Vacuum—There Is Something in It." The point of this lecture was, of course, that even our most perfect vacuums are filled with countless millions of atoms and electrons. Some time afterwards at another occasion in a lecture which he called "Matter—Is There Anything In It?" he pointed out, as we have done in the previous articles of this series, that the stuff which we call matter, consists almost entirely of space. The space occupied by the nucleus and the external electrons

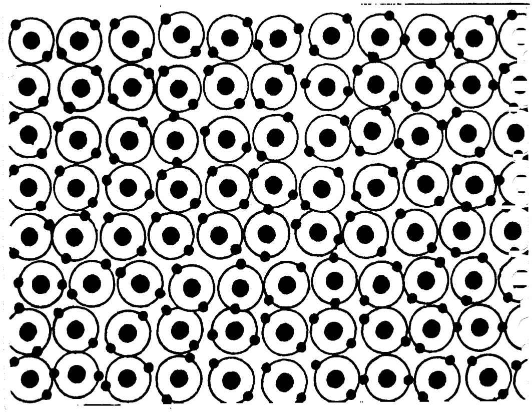

FIG. 9. DIAGRAMMATIC REPRESENTATION OF THE ARRANGEMENT OF MOLECULES IN A SOLID

This represents the arrangement of water molecules in the solid state, i. e., ice Each molecule consists of one atom of oxygen with two of hydrogen. These are arranged in close proximity, limiting their movement to a small space.

of even the most complex atoms is extremely small compared to the size of the atom as a whole. Since all matter is composed of atoms, it follows that matter is mostly space.

This is of interest in our study of electricity because electricity, as we are ordinarily aware of it, is nearly always associated with matter and if matter consists mostly of space it will be necessary to find out how the electric current manages to flow through or across this space. Electricity, is not always associated with matter, however, as will be seen when we investigate its action in the vacuum tube; in fact, it was only when electricity was first observed apart from matter, i. e., in the vacuum tube, that its true nature began to be suspected. As long as it was confined to solid and liquid conductors, the mystery of electricity was inextricably merged with the mystery of matter. Once, one was observed apart from the other, each became the basis for the explanation of the other.

MATTER MADE UP MOSTLY OF SPACE

Thus far, we have considered matter only from the viewpoint of its constituent elements, the atom and the electrons. When we come to consider matter in the aggregate, we find that here, too, empty space enters in to a considerable extent. The molecular structure of matter is such that no two atoms or molecules are in permanent contact with one another. Each molecule is separated from its neighbors by a space, inconceivably small as measured by ordinary standards, yet very large compared to the size of the electron. At ordinary temperatures, these molecules are in constant state of agitation, each undergoing millions of oscillations per second and colliding with its neighbors as often. Heat, as we know it, is in reality a manifestation of this vibration.

As a body is warmed, more energy is imparted to the molecules and they vibrate more actively; as a consequence, the force of collision between molecules is greater and they tend to occupy more space. This makes the body become larger as it is warmed, a phenomenon we ordinarily term thermal expansion.

THREE STATES OF MATTER ACCOUNTED FOR BY MOLECULAR ACTIVITY

Matter may exist in either of three states: 1, as a solid; 2, as a liquid, and 3, as a gas, depending upon the temperature. At low temperatures, all matter becomes solid while at high temperatures it becomes gaseous. As the heat energy content of a body is progressively increased, it passes from a solid into a liquid and finally into a gaseous state.

In solids, the molecules are relatively close together and are bound together by powerful attractive forces. While there is incessant agitation among the molecules, they make only small excursions from their mean position. As the temperature is increased, the agitation of the molecules is increased, the mean free path between collisions becomes longer and the cohesive force between them is almost lost. Naturally, liquids will assume the shape of any vessel into which they are placed. With a still further increase in temperature or heat energy content, the cohesive force between molecules is lost entirely and they tend to knock one another as far apart as possible. When this condition is reached, the body is in the gaseous state and the molecules will no longer remain within the vessel in which they are placed unless restrained by solid walls. The combined force of all the molecules impinging against the sides of the containing vessel in the case of a gas, is a measure of the gas pressures. The greater the number of molecules per unit of volume and the greater their speed (and also their kinetic energy) the greater will be the pressure. This in brief is the kinetic theory of gases.

Thus the three states of matter are simply accounted for by the difference in molecular agitation. In different elements, the transition points between the solid, liquid and gas states vary greatly. In the case of helium, the transition point between liquid and solid is 271 deg. below zero, Centigrade, while with tungsten, it is 3400 deg. above zero, Centigrade. Water, at atmospheric pressure, passes into a gas at 100 deg. Centigrade, while for platinum a temperature of 3910 deg. C. is necessary. In each of these cases, however, the principles underlying the changes are the same.

In considering matter as a conductor or carrier of electricity, we have three classes of conductors, solid, liquid and gaseous. The type of conductor we are most familiar with, of course, is the solid conductor, usually in the form of copper wire or cable. Conductors of the second class are those to be found in primary and sec-

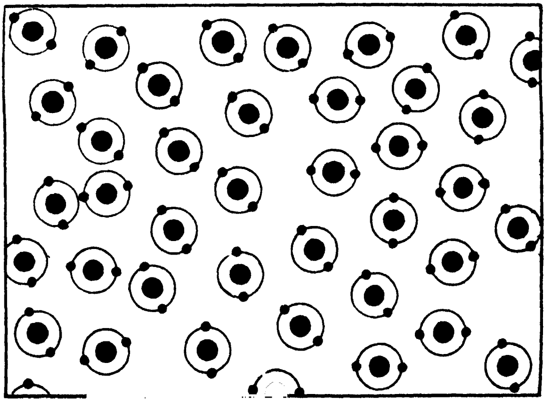

FIG 10. MOLECULES OF WATER IN THE LIQUID STATE

Here, compared with Fig. 1, the molecules are farther apart and the attractive force between them has almost disappeared.

ondary electric batteries, electrolytic rectifiers and condensers, and in electroplating apparatus. The third class of conductor is best exemplified by the mercury vapor lamp and the electric arc.

As indicated in Chapter I, in the early days of electrical service it was difficult to reconcile the theories which had been developed for conduction in solids and in liquids. Two theories had been developed, neither of which would fit the other case. It was not until the third class of conduction began to receive attention, and then only because it became apparent that there was still another class of conduction, if it might be called such, which depended upon neither of the three types of conductors, but involved what was apparently a fourth state of matter, that a logical explanation was forthcoming. It seemed that the electric current was able to bridge spaces where there was no matter. This, as has been pointed out, led first to the conception of the electron and finally to its discovery.

We have, in the course of this discussion, referred to the attractive forces between atoms and molecules and electrons. Now when we speak of force, most of us think we know what the term means, but when we try to define it and to form an idea of it in our minds, we are compelled to admit that the idea of force is somewhat vague. Force is entirely a subjective concept without any reality. When we cause a body to alter its state of motion, either by changing its speed or its direction, we say that we exert a force. Yet, the body after the application of this force has undergone no change except in the total amount of available energy it may possess. Whatever may be the alteration in the body due to the application of a force, the alteration is but the manifestation of a change in the disposition or availability of that incomprehensible entity we call energy.

So, in our consideration of electricity and the structure of matter, it is necessary to include the concept of

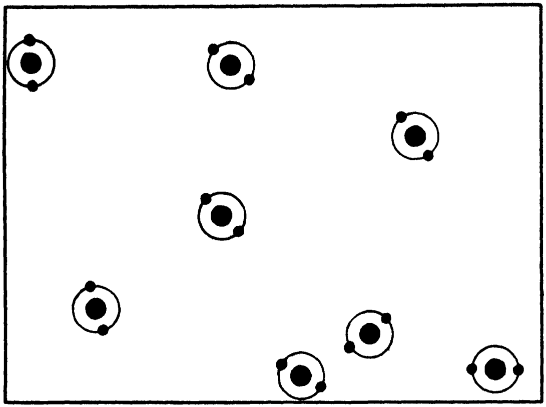

FIG. 11. MOLECULES OF WATER IN THE GASEOUS STATE

In the gaseous state all attractive force between the molecules has disappeared and they are spaced at relatively great distances.

energy. Energy and electrons, in fact, are the two entities in terms of which all things in the universe must be explained. These two entities, furthermore, are probably convertible. The idea that energy may be converted into matter and vice versa is relatively new but, no doubt, will have far-reaching results upon future scientific thought. Already it seems to give us the clue to the secret of the sun's energy.

It seems that to every particle of moving matter in the universe must be ascribed a certain amount of energy. The amount of energy possessed by any particle depends upon its speed relative to other particles, and its electrical characteristics. Thus, when we speak of forces existing between atoms and molecules and electrons, we are referring to the relative available energy they possess. Two atoms, for instance, attract each other with a certain definite force. If no other restraining forces are acting upon these atoms and if they are permitted to come together, a certain amount of energy will be liberated. Similarly, to pull the two atoms apart requires the expenditure of a certain definite amount of energy.

In the case of hydrogen, for instance, at ordinary temperatures, the atoms of hydrogen always combine in pairs to form molecules. At extremely high temperatures, however, the molecule is dissociated into single atoms, which, however, will recombine into molecules of two atoms each when the temperature decreases. This fact is made use of in the recently developed atomic hydrogen welding process. In this process, a stream of hydrogen gas is forced under pressure between the electrodes of a powerful electric arc. In the arc, due to the extreme temperature, the normal hydrogen molecules are dissociated into single atoms of hydrogen and in this state are forced beyond the limits of the arc. Once outside of the arc the temperature drops and because of this the separate atoms of hydrogen combine again into molecules of two atoms each. In this recombination, they

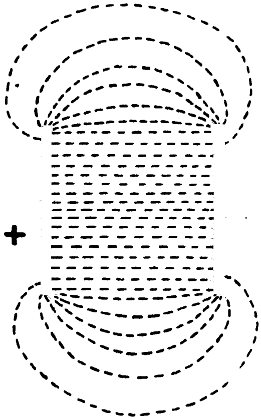

FIG. 12. THE ELECTRIC FIELD EXISTING BETWEEN TWO OPPOSITELY CHARGED METAL PLATES

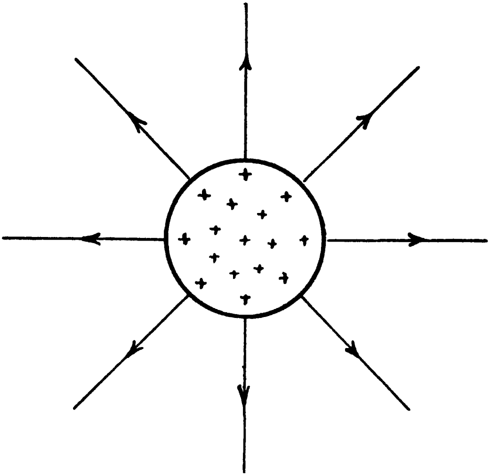

FIG. 13. THE ELECTRIC FIELD SURROUNDING A CHARGED METAL SPHERE ISOLATED IN SPACE

release the energy which was absorbed in the process of dissociation in the electric arc, resulting in the production of extremely high temperatures.

One of the things we are interested in in our study of electricity, is the nature of the force which enables atoms and electrons to attract or repel each other. In what way is the force between two such elements transmitted across the space which separates them?

It has been shown that when a stick of sealing wax is rubbed with a piece of flannel, both the flannel and the wax become charged, one negatively and the other positively. This charge, we know, is due to some of the electrons having been rubbed off the atoms composing the flannel and left on those of the wax.

If now the wax is approached to the flannel, it will be found that an attractive force exists between the two. This force exerts itself even though the two substances are not in actual contact.

The effect is even better illustrated by suspending a light substance such as a pith ball from a fine thread and touching it with a charged body, say the stick of sealing wax. It will be found that the pith ball becomes charged with electricity of the same polarity as that of the wax, and since like charges repel each other, the pith ball will be repelled by the sealing wax. By experimenting, it will be found that the repulsive force is present even though the pith ball and the wax are at a considerable distance from each other. Evidently the space surrounding the charged bodies is under some kind of strain which enables it to act upon the charged

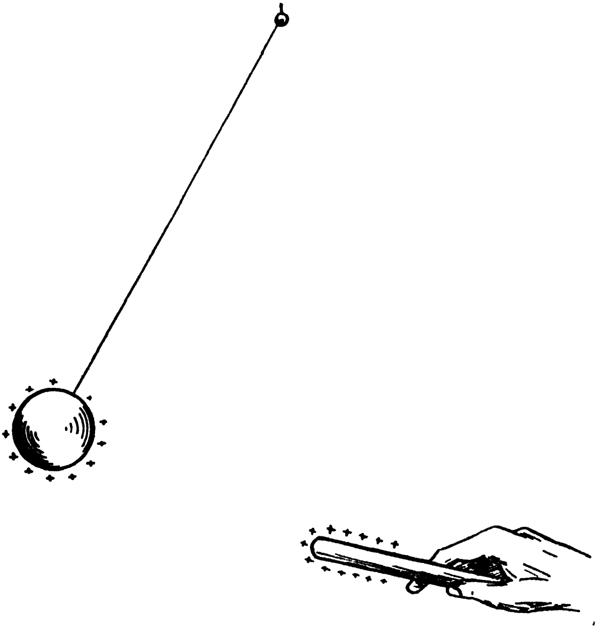

FIG. 14. CHARGED PITH BALL SUSPENDED FROM A THREAD IS REPELLED BY STICK OF SEALING WAX CHARGED WITH ELECTRICITY OF SAME POLARITY

bodies with a force, attractive or repulsive depending upon the relative polarities of the charges. This space surrounding a charged body, in which another charged body is acted upon by a force tending to move it, constitutes an electric field, sometimes called an electrostatic field.

LINES OF FORCE AND THE ELECTRIC FIELD

The exact nature of an electric field is not known, but it is convenient to think of it in terms of lines stretched between the oppositely charged elements. The direction of the line, properly drawn, gives the direction of the force at any point and their closeness to each other shows the relative strength.

In Fig. 12 is illustrated the electric field between two oppositely charged metal plates. Directly between the two plates the lines of force are straight and are also most intense. At the edges, the lines are curved and less numerous, indicating a field of lower intensity.

Figure 13 shows a positively charged metal ball, which we may conceive as being isolated in space, far from any other charged bodies. Under this condition the lines of force are shown extending radially outward from the sphere. The arrows on the lines indicate the direction in which a positive charge would be urged if placed in that portion of the field. While the lines are shown ending in uncharged space, in reality each line would terminate somewhere upon a negative charge.

Whether any such lines of force as we have described actually exist and if they do, what medium they are composed of, nobody knows at present. At one time, before the days of Einstein, we used to believe—for now we are not sure whether we believe it or not—that these lines were lines of strain in the ether. The ether was a hypothetical medium which was supposed to exist throughout all space, even between the atoms and between the electrons of all matter.

Since the more or less general acceptance of the Einstein theory and the quantum theory, the need for this ether is not so essential as it once was, although the ether theory cannot yet be said to have been superseded.

For the present, however, it will be convenient to assume the existence of the lines of force, since such an assumption will be helpful in explaining electrical phenomena. Each electron, that is each unit electric charge in the universe, it will be assumed, has attached to it lines of force which enable it to act at a distance upon other oppositely charged elements. This conception will not only enable us to overcome some of the difficulties of explaining "vacuums with something in them" and "matters with nothing in them", but will also give us a means of accounting for the operation of generators and motors and electric door bells.

CHAPTER VI

ELECTRIC CONDUCTION THROUGH GASES

ONE OF THE fundamental tendencies in nature is the tendency towards equilibrium or the equalization of opposites. This is true particularly with regard to energy. When two bodies of different temperatures are placed together with a conducting medium between, the warmer body becomes cool and the cooler body becomes warm until, finally, both have the same temperature. The excess heat energy of the warm body is given up to the cool body until a condition of equilibrium is obtained. In other words, heat energy seeks a lower level in the same way that water or any body elevated above the earth against the force of gravity seeks a lower level. This flow of heat from a high to a low level is, in fact, merely an infinitesimal decrement in the general lowering of the total heat or energy level of the universe.

Shortly after the establishment of the principle of the conservation of energy in the middle of the last century and the recognition of the fact that all the different forms of energy are mutually convertible, one into another, it was also found that the conversion did not work equally well in both directions. Energy in any form it was found could readily be converted into heat but when heat energy was converted back into other forms there was never quite as much left as there had been originally. Some of the energy remained as heat. Once energy is in the form of heat, it is impossible to get all of it out again. This is purely an empirical fact, for which no theoretical necessity has ever been shown. It forms the basis of the second law of thermodynamics.

THE DEATH OF HEAT

If this law is true, it would seem that the total energy of the universe is gradually being transformed into heat and this heat is gradually seeking a lower level. The energy of the universe is in a continual state of transformation. Whether it be in the formation of new stars or of planets, or in the production of heat underneath our boilers, or in the production of rotating torque in our motors, energy is being transformed, but with each transformation, a little of it appears as heat. This heat tends to seek a lower level.

Unless other factors enter in of which we have no knowledge, therefore, at some time far in the distant

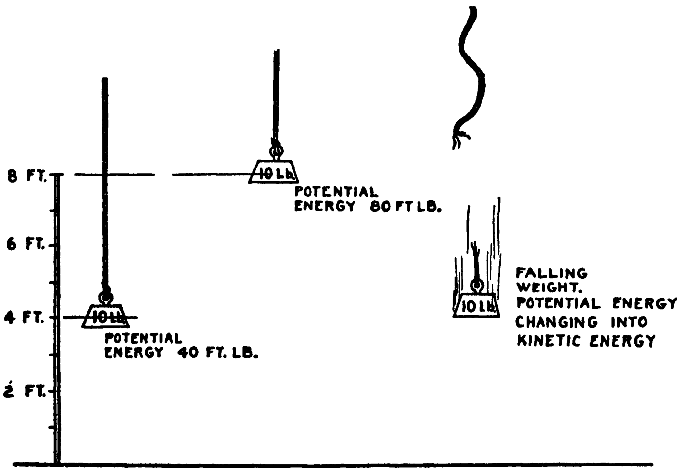
8 FT.
6 FT.
4 FT.
2 FT.
10 LB.
POTENTIAL ENERGY 80 FT LB.
10 LB.
POTENTIAL ENERGY 40 FT. LB.
10 LB.
FALLING WEIGHT. POTENTIAL ENERGY CHANGING INTO KINETIC ENERGY

FIG. 15. DIAGRAM SHOWING HOW POTENTIAL ENERGY IS STORED IN A BODY BY VIRTUE OF ITS ELEVATION ABOVE GROUND

A 10-lb. weight raised 4 ft. above the ground has potential energy equal to 10 × 4 or 40 ft. lb. At 8 ft. elevation, its potential energy has doubled. If the weight is permitted to fall, the potential energy stored in it is converted in kinetic energy. The instant it touches the ground, its potential energy is zero but its kinetic energy is a maximum.

future, all of the energy in the universe will have been transformed into heat and this heat will have reached its lowest level. The same temperature will exist everywhere. Clausius calls this final state "Warmetod" (death of heat); and the relentless process of degradation which leads up to it was called by Kelvin the "dissipation of energy."

This idea is not new as pointed out by Paul Heyl of the Bureau of Standards.[1] The ancient myths of our Nordic race speak of the coming of a time when both gods and men will sink into an endless, deathless sleep; when upon them all, both in Asgard and upon earth, shall descend the twilight, the evening, the everlasting night. This was called by the old German's "Götterdämmerung," "The twilight of the gods," and from it is taken the inspiration for one of Wagner's operas. Translated into the jargon of the physicist "Götterdämmerung" means "The entropy of the universe tends towards a maximum and its available energy towards a minimum."

So it is evident that the flow of energy from a high to a low level is a manifestation of a great universal law. While what has been stated in the few preceding paragraphs is of only general interest here, it will be well to keep these facts in mind since in considering electrical phenomena we are always dealing with energy transformations.

NEUTRALIZATION OF ELECTRIC CHARGES DUE TO FLOW OF ENERGY FROM HIGH TO A LOW POINT

It will be recalled that in the illustration of imparting electrical charges by means of sealing wax and flannel, the opposite charges tended to neutralize each other. This is simply another illustration of energy seeking a lower level.

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[1] Scientific Monthly, July, 1924.

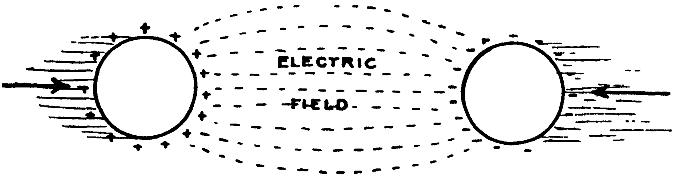

FIG. 16. TWO ELECTRICALLY CHARGED BODIES MOVING TOWARD EACH OTHER UNDER THE ATTRACTIVE INFLUENCE OF THE FIELD BETWEEN THEM

When the opposite charges were placed on the wax and flannel and the two substances separated, work was done in separating the bodies against the attractive influence due to the electric field. The two charged bodies, separated in this way possess potential energy in the same way that a body raised above the earth possesses potential energy by virtue of its elevation. In the case of the body above the earth the measure of the potential energy is the product of the mass of the body by the distance through which it has been raised. In the case of electrical charges, the potential energy is

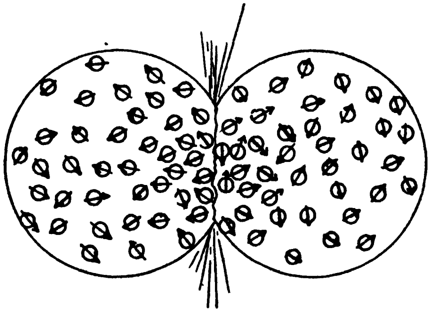

FIG. 17. AT THE INSTANT OF COLLISION OF THE TWO BODIES, THE KINETIC ENERGY WHICH THEY POSSESSED IS PASSED ON TO THE ATOMIC AND MOLECULAR SYSTEMS OF WHICH THEY ARE COMPOSED. THIS MANIFESTS ITSELF IN HAPHAZARD MOTION AMONG THE MOLECULES WHICH WE RECOGNIZE AS HEAT

measured in terms of the value of the charges producing the electric field and the distance between them. It may be thought of either as the amount of energy originally required to produce separation of the two bodies or the energy released when the two charges are neutralized, that is, when the excess of negative electrons on one body is returned to the positively charged atoms of the other body.

When two such oppositely charged bodies are permitted to move toward each other under the attractive force of the field between them, the potential energy of the bodies is gradually transformed into kinetic energy as the speed is accelerated.

At the moment they meet, or rather just before they meet, all the potential energy of the bodies has been transformed into kinetic energy and at the instant of impact this kinetic energy is delivered to the invisible molecules, atoms and electrons constituting the two bodies. This addition of energy imparts to the molecules and atoms of the bodies, haphazard motions which, as explained in Chapter V, we recognize as heat. As the charged bodies come together, the excess negative electrons on the negatively charged body unite with the excess protons on the positively charged body, forming normal atoms and thereby effecting complete neutralization.

The action just described and the energy relations involved in the separation and return of electrical charges lie at the base of all electrical phenomena with which we are familiar in everyday life. As pointed out previously, electrical phenomena manifest themselves only when unsatisfied atomic systems are brought into existence. Most of the atoms in the universe are satisfied and are therefore unaccompanied by electrical phenomena. Just as soon, however, as an electron is separated from an atom whose needs demand its pres-

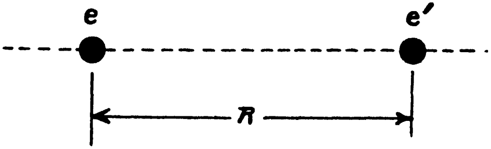

FIG. 18. TWO CHARGES e AND e′ SITUATED AT A DISTANCE R FROM EACH OTHER WILL ACT UPON EACH OTHER ALONG THE LINE e-e′ WITH A FORCE f ACCORDING TO THE FORMULA: $f = e\,e' \div R^2$

ence, an electric field is set up between the unsatisfied systems which tends to bring them together.

THEORY OF CONDUCTION THROUGH GASES

In effecting neutralization of opposite charges of electricity in this manner, it is not necessary that the two bodies carrying the charges actually be brought together. The bodies carrying the charge may, and usually do, possess billions of normal atoms which play no part in the action. If the excess electrons on the negatively charged body could be removed and carried over to the positively charged body, or the excess protons could be removed from the positively charged body and carried to the negatively charged body, satisfaction would be just as complete.

The electric field existing between electrically charged bodies acts only upon the dissimilar charges by virtue of which it exists; it does not act upon the normal atoms or molecules of which the charged bodies may be composed and upon whose unsuspecting systems the divorced electrons have been lodged. Therefore if a means is provided to conduct the excess electrons back to their original family circle, the normal atoms need not be disturbed.

This process of carrying electric charges of one sign to those of the opposite sign to effect neutralization, regardless of the manner in which it is accomplished, is called conduction. It may or may not be done with the aid of normal atoms although the latter, when they are impressed into service, often facilitate the process considerably. In a vacuum, the electrons or protons can pass bodily between the charged bodies along the lines of force constituting the electric field.

An electron, for instance, placed in an electric field in vacuum, will be urged in the direction of the positive charge producing the field. The force acting upon such an electron will depend upon the strength of the charge producing the field and the distance from this charge that the electron is placed. The force will vary with different positions of the electron with respect to the charge.

POTENTIAL GRADIENT AND COULOMB'S LAW

In order to make this clear, we must consider what is known as the potential gradient. When two electric charges are concentrated at two points, isolated from all material supports and placed in empty space, the values of the charges being e and e′ respectively, and R, representing the distance between them as shown in Fig. 18, each charge will exert upon the other a force, f, along the line e e′. Numerically this force is given by the following equation:

$$f = e\,e' \div R^2$$

This law is known as Coulomb's law and, as may be noted, somewhat resembles the law expressing the force between two bodies due to the gravitational attraction between them. It is obvious from the equation, that if both charges are of the same polarity, that is, both positive or both negative, the value of the force will be positive, corresponding to a repelling force. If the charges are of opposite polarity, the force will be negative or attractive.

If one of the charges e or e′ in the above equation is a unit charge, that is having a value of one, it will be seen that the expression becomes $f = e \div R^2$. This equation, then, gives the force exerted by an electric field due to a charge e, upon a unit charge at any point in space. It expresses the peculiar state of the medium (in this case, the ether) due to the existence of the charge e, whereby the medium has the ability to exert a force on any charge which may be present by displacing the latter. This implies that the potential energy stored in a system of electric charges lies not in the bodies themselves, but in the medium that lies between them.

VARIATION OF FORCE DUE TO ELECTRIC CHARGE

This was pointed out by Faraday almost a hundred years ago. It seems as though the medium surrounding an electric charge is stressed, so to speak, and a certain amount of potential energy is stored in it, which is capable of doing work whenever another charge is placed in the field and permitted to move under its action. The amount of energy available at any point is called the potential of that point and depends upon the value of the charge producing the field and the distance of the point in question from this charge.

In Fig. 19, with the aid of Coulomb's equation, we have shown how the value of the potential varies with distance from the charge. If we draw concentric circles around the charge, it is evident from the equation that the value of the potential is the same for any point on a particular circle; which of course applies equally well to the points on the surfaces of concentric spheres. Because of the inverse square variation of the force with distance, the potential increases rapidly as the charge producing the field is approached. Thus an electron, placed in the field close to the charge will be accelerated much more rapidly than it would if placed at some distance from the charge.

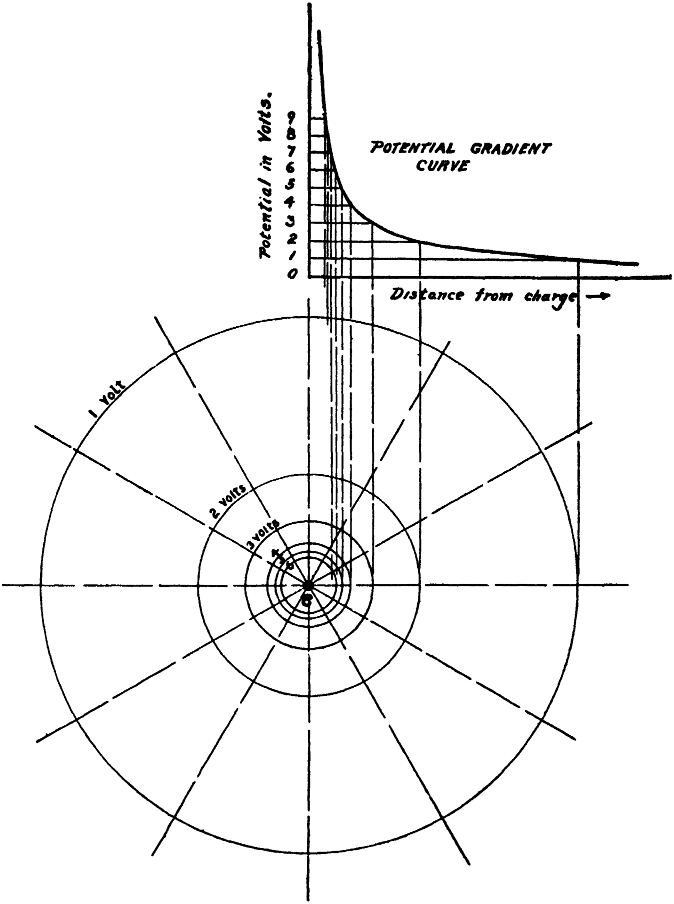

FIG. 19. THE VOLTAGE GRADIENT CURVE, AND METHOD OF PLOTTING IT

Below are shown a number of concentric circles which represent equipotential points around the charge, e. Due to the fact that the force due to the charge varies inversely as the square of the distance, the circles, it will be noted are not spaced equal distances apart.

Now the curve representing the various values of potential at various distances from the charge is called the potential gradient curve. Its value at any point determines the speed at which an electron will fall, so to speak, towards the positive charge. As the electron approaches the positive charge, it acquires kinetic energy but its potential energy is decreased. At steep places in the potential gradient curve, the conversion of potential energy into kinetic energy is rapid, while at other places where the grade is easy, conversion is slow.

It must be understood that the total amount of potential energy available to a charge located at a particular point in the field is the same, regardless of the manner in which the charge is neutralized.

It does not matter in which manner or by what path the charge is conducted from a place of maximum potential energy to one of zero potential energy. Just as a weight lifted above the earth against gravity possesses a certain definite amount of potential energy due to its position regardless of how this potential energy is recovered, so an electric charge in an electric field also possesses a definite amount of potential energy due to its position regardless of the method of recovery. The rate at which the potential energy of a charge is transformed into kinetic energy or the rate at which it is accelerated depends upon the potential gradient of the field, just as the rate at which the potential energy in a body elevated above the earth is converted into kinetic energy depends upon the steepness of the path down which it travels. Potential gradient is measured in terms of volts per inch or centimeter in the same way that the grade of a railroad or automobile road is measured in terms of feet rise per mile or per 100 ft.

Having given some of the facts regarding the manner in which electrical charges can be neutralized and

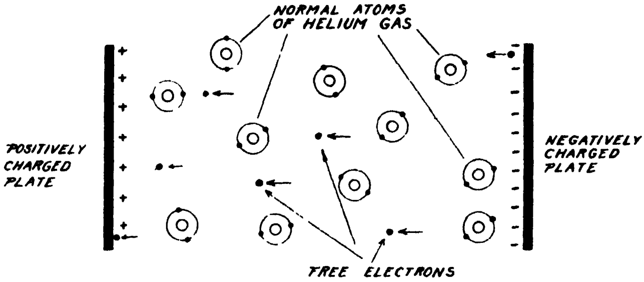

FIG. 20. CONDITIONS BETWEEN TWO OPPOSITELY CHARGED PLATES AN INSTANT AFTER THE CHARGE IS APPLIED

In addition to the normal helium atoms existing between the plates there are a few free electrons. The normal atoms are unaffected by the electric field due to the charge but the free electrons are drawn towards the positive plate. Their velocity will increase as they approach the plate.

the forces involved, let us now consider what actually happens when two oppositely charged plates are placed a short distance apart. According to our previous explanation of electric charges, one of the plates will carry a number of atoms which lack the required number of electrons, that is they have excess protons while the other plate will have more electrons than that necessary to satisfy the requirements of the atomic systems of which it is composed. Due to this unequal distribution of electrons and protons among the atoms of both plates an electric field will exist between the plates.

Under these conditions, neutralization of the charges may be brought about in three ways: First, the excess electrons on the negative plate may travel across the space to the positive plate; second, the excess protons on the positive plate may be transferred to the negative plate and, third, some of the molecules of gas between the two plates may be impressed into service to effect the interchange of protons. In a perfect vacuum of course, only the first two methods would be possible.

The third method is the most usual and also the most interesting.

Normal atoms and molecules as has been pointed out play no part in electrical phenomena and if only normal atoms or molecules of gas exist between the charged plates, nothing happens. If in addition to the normal atoms, however, there are a number of free electrons, that is, electrons which are not attached to any atoms and which lead a more or less bachelor existence, things become interesting. These electrons, being free to move, are acted upon by the electric field and are drawn to the positive plate at a speed which depends upon the potential gradient of the field.

As the free electrons are accelerated toward the positive plate occasionally, one of these normal gas atoms may lie in its path, and if the speed of the electron is high enough the force of the collision may be sufficient to knock one of the external electrons out of the normal atom. Now, if you recall, in chapter two of this book, we showed that when a neutral atom loses an external electron, the atom is said to be ionized, and is positively charged.

So if such a collision of a free electron and a normal atom occurs, and it happens quite often, in addition to the free electron which did the damage, we now have a positively charged atom and another free electron. Under the influence of the electric field, the two electrons are drawn to the positive plate and the positively charged atom is drawn to the negative plate. The latter, however, moves much more slowly than the former due to its much greater size.

Under the continued action of the electric field, the two free electrons (together with many others which have gone through a similar procedure) are accelerated towards the positive plate and again collide with normal atoms, knocking more electrons off. As might be expected, the process is cumulative, resulting in an ever increasing number of free electrons, and positively charged atoms. The electrons finally reach the positive plate where they combine with the unsatisfied atomic systems, thus neutralizing the charge. The positively charged gas atoms pass to the negative plate where they acquire from the plate an excess electron, thus reducing the negative charge from the plate and becoming normal atoms of gas again.

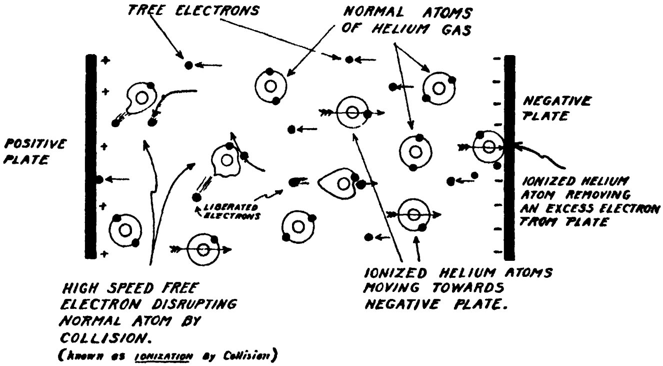
TREE ELECTRONS
NORMAL ATOMS OF HELIUM GAS
POSITIVE PLATE
NEGATIVE PLATE
IONIZED HELIUM ATOM REMOVING AN EXCESS ELECTRON TROM PLATE
LIBERATED ELECTRONS
HIGH SPEED FREE ELECTRON DISRUPTING NORMAL ATOM BY COLLISION.
(known as IONIZATION by Collision)
IONIZED HELIUM ATOMS MOVING TOWARDS NEGATIVE PLATE.

FIG. 21. CONDITIONS BETWEEN THE CHARGED PLATES SHOWN IN FIG. 20 AFTER THE CHARGE HAS BEEN ON A SHORT TIME

Due to the accelerating action of the field upon the free electrons, a number of the latter have collided with normal gas atoms in their path and have knocked external electrons out of the orbits of the neutral atoms. This imparts a positive charge to the atom and it at once moves towards the negative plate under the action of the electric field. Normal atoms which have not been disrupted in this manner are unaffected. This process of knocking electrons off normal atoms is called ionization. The liberated electrons together with the free electrons responsible for their freedom move toward the positive plate where they neutralize the positive charge.

In this manner, it will be seen that the existence of a few free electrons between the charged plates can, by disturbing the satisfaction of normal atoms between the plates, impress the latter into service for bringing about neutralization of the charge on the plates. This is called gaseous conduction and explains why electricity can flow across a gas space between oppositely charged poles or electrodes.

In the above explanation, we have assumed the existence of a number of free electrons in the space between the charged plates. This might seem an unjustified assumption but actually it is not. In the gases of the atmosphere, there are nearly always some free electrons present. How these free electrons originate is a vast subject in itself and will be dealt with in later articles. They are being produced constantly and normally combine with positively charged gas atoms at the same rate that they are produced.

Other interesting things happen in the space between the charged plates which have a bearing upon the conducting properties of a gas and these will be taken up in the following chapter.

CHAPTER VII

CONDUCTION IN LIQUIDS

IN OUR DISCUSSION of electric conduction through gases in the preceding chapter, it was shown that a gas was rendered conducting if we introduced among the molecules of gas, a number of free electrons. These "unattached" electrons moving under the action of the electric field between oppositely charged plates ionized neutral atoms of gas, thus producing additional free electrons as well as positive ions, both of which are effective in causing the discharge of the plates. If, by means of an electric battery or a dynamo, the plates are maintained in a continuously charged condition, an electric current will be maintained across the gas space.

This type of electric conduction is known as ionic conduction because it makes use of ions, that is, electrically charged atoms of matter. It will be remembered, however, that we considered also, rather briefly, the case where no normal atoms of gas were present between the plates, that is, in a perfect vacuum, and where conduction was effected entirely by the transference of electrons from the negatively charged plate to the one carrying the positive charge. This type of conduction is known as electronic conduction to differentiate it from ionic conduction. All processes of conduction, whether in gases, in solids, in liquids or in vacuum, can be classified under either of these headings.

While, in a general way, ionic conduction may be thought of as applying to gases and liquids and electronic conduction as applying more particularly to solids, this is strictly not true. There are solid bodies that conduct electronically and others that conduct ionically; both ionic and electronic conduction takes place in gases, and finally there are liquids which con-

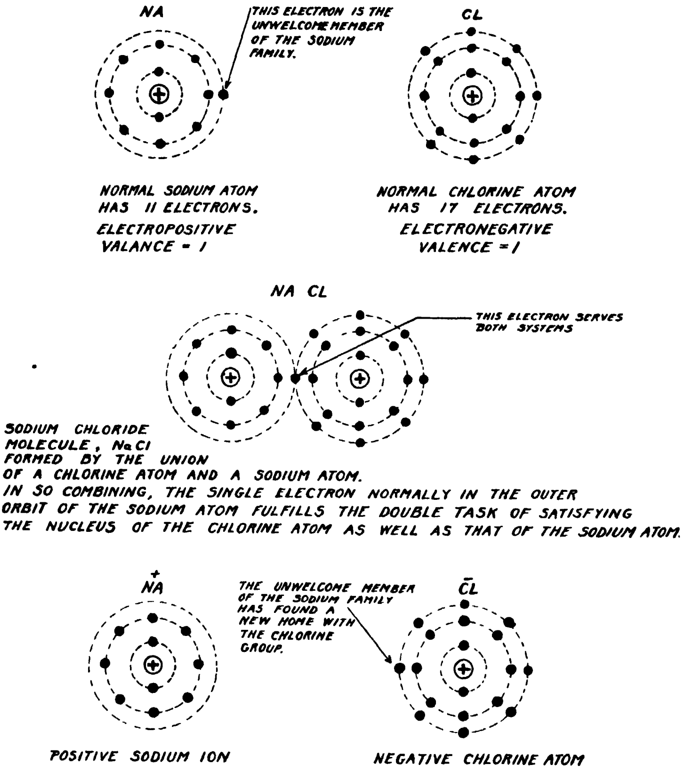
NA
THIS ELECTRON IS THE UNWELCOME MEMBER OF THE SODIUM FAMILY.
CL
NORMAL SODIUM ATOM HAS 11 ELECTRONS.
ELECTROPOSITIVE VALANCE = 1
NORMAL CHLORINE ATOM HAS 17 ELECTRONS.
ELECTRONEGATIVE VALENCE = 1
NA CL
THIS ELECTRON SERVES BOTH SYSTEMS
SODIUM CHLORIDE MOLECULE, NaCl FORMED BY THE UNION OF A CHLORINE ATOM AND A SODIUM ATOM.
IN SO COMBINING, THE SINGLE ELECTRON NORMALLY IN THE OUTER ORBIT OF THE SODIUM ATOM FULFILLS THE DOUBLE TASK OF SATISFYING THE NUCLEUS OF THE CHLORINE ATOM AS WELL AS THAT OF THE SODIUM ATOM.
+ NA
THE UNWELCOME MEMBER OF THE SODIUM FAMILY HAS FOUND A NEW HOME WITH THE CHLORINE GROUP.
− CL
POSITIVE SODIUM ION
NEGATIVE CHLORINE ATOM

FIG. 22. ATOMIC ARRANGEMENT OF THE SODIUM CHLORIDE MOLECULE SHOWING THE PROCESS OF IONIZATION DUE TO DISSOCIATION

The normal sodium atom has one electron in its outer orbit which it would like to lose. The chlorine atom on the other hand lacks one electron in the outer orbit to give the system stability. As a consequence these two atoms readily combine to form the molecule of salt shown at the center. In dissociation the salt molecule splits up again but the chlorine atom retains the single electron from the outer orbit of the sodium atom. The residue of the sodium atom is left with a positive charge while the chlorine ion has a negative charge.

duct electronically and others again that are conductive ionically.

WHAT IS AN ION?

In referring to ionic conduction, it may be well to digress a moment to discuss more fully the term ion, since there may be some misunderstanding if the definition of an ion is not clear. In accordance with the original use of the word "ion" by Faraday, an electron is an ion. In the Greek, "ion" means "goer" or

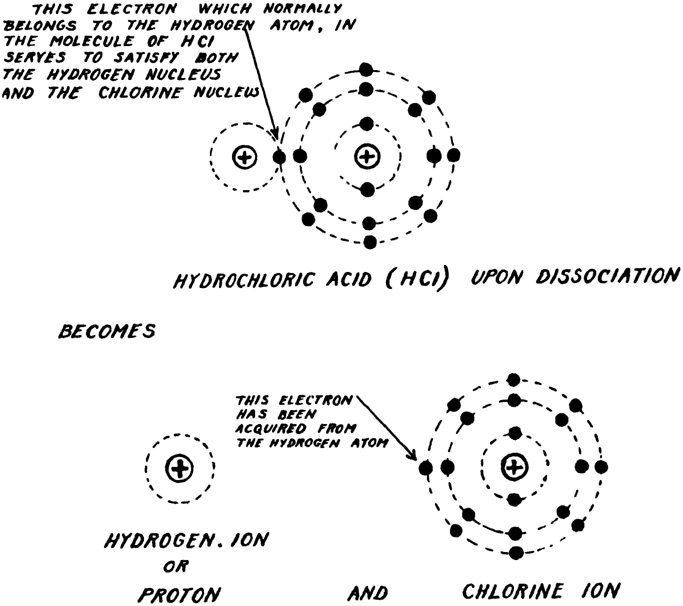
THIS ELECTRON WHICH NORMALLY BELONGS TO THE HYDROGEN ATOM, IN THE MOLECULE OF HCl SERVES TO SATISFY BOTH THE HYDROGEN NUCLEUS AND THE CHLORINE NUCLEUS
HYDROCHLORIC ACID (HCl) UPON DISSOCIATION
BECOMES
THIS ELECTRON HAS BEEN ACQUIRED FROM THE HYDROGEN ATOM
HYDROGEN. ION OR PROTON
AND
CHLORINE ION

FIG. 23. AN ACID ALWAYS PRODUCES POSITIVELY CHARGED HYDROGEN IONS AS ONE PRODUCT OF DISSOCIATION

In the case of hydrochloric acid (HCl) shown above which is formed by the union of an atom of hydrogen with an atom of chlorine, upon dissociation the chlorine atom retains the single external electron which originally belonged to the hydrogen atom. This leaves of the latter, only the nucleus which is the proton.

"traveler," so Faraday, in thinking of the charge as carried by an atom, called the charged atoms, ions. Any ultimate carrier of an electric charge was called an ion.

Whether an electron, which is now known to be itself the ultimate electric charge, can be classified as an ion by this definition, depends upon how the word carrier is interpreted. If the word carrier is taken literally, an electron, which does not carry anything but itself, cannot be considered as an ion. If the original term "goer" is applied, however, an electron is as much an ion as is a positively or negatively charged atom. In general, however, the term ion is applied only to an atom or molecule or group of molecules having more or less than the normal number of electrons. In this book, an electron will not be referred to as an ion.

IONIC CONDUCTION INVOLVES TRANSPORT OF MATTER

The principal characteristic of ionic conduction is the movement or transport of matter. In the explanation of conduction through gases, it was seen that conduction of electricity was accompanied also by an actual movement of atoms of Helium gas. True, these atoms had lost an external electron but as has been explained[1] the loss of an external electron does not fundamentally alter the atom.

This characteristic is more marked in conduction through liquids than it is in conduction through gases. In many liquids, dissociation occurs, that is, the molecules of such liquids or salts in solution are broken up into their constituent atoms or molecules. An example of this is had when sodium chloride (common salt) is dissolved in water.

Sodium chloride, NaCl, it will be recalled, is formed by the combination of the electropositive atom of sodium, Na having one excess electron, with the electro-

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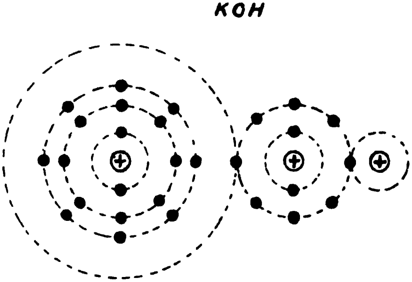
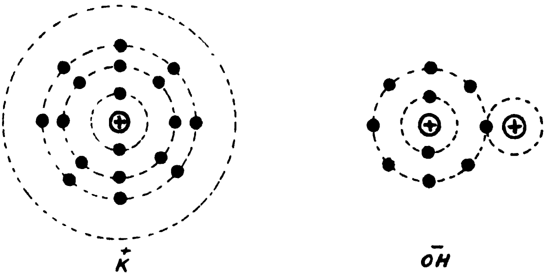
[1] Page 60.



MOLECULE OF POTASSIUM HYDROXIDE (KOH)
THE NORMAL ATOM OF POTASSIUM (K) HAS 1 ELECTRON IN THE 4TH. ORBIT. THIS ELECTRON SERVES TO SATISFY THE NUCLEUS OF THE POTASSIUM ATOM AS WELL AS THAT OF THE OXYGEN ATOM, WHICH NORMALLY HAS ONLY 6 ELECTRONS IN THE OUTER ORBIT. THE SINGLE ELECTRON OF THE HYDROGEN ATOM SERVES A SIMILAR FUNCTION.



THIS ATOM HAS LOST ITS OUTERMOST ELECTRON

THIS ION HAS CAPTURED THE ELECTRON BELONGING TO THE POTASSIUM ATOM

FIG. 24. POTASSIUM HYDROXIDE IS A BASE. IN DISSOCIATING IT YIELDS THE NEGATIVE ION OH.

The atom of oxygen which takes part in this union has only 6 electrons in its outer orbit where 8 would make a stable system. Hence it has an affinity for two electrons. For these reasons it combines readily with the potassium atom which has an electron to spare and with the hydrogen which also extends the loan of an electron. In dissociating, however, the oxygen and hydrogen atoms remain together, and retain the extra electron formerly belonging to the potassium atom. This gives the latter a positive charge and the OH ion a negative charge.

negative atom of Chlorine, Cl which lacks an electron. When this salt is dissolved in water, some of its molecules separate into two parts, one of which has the nucleus of the sodium atom and the other that of the chlorine atom. The number of external electrons around each of these nuclei is, however, not that of the normal atom. In the process of separating, the chlorine atom has failed to return the external electron which it borrowed from the sodium atom when it combined with the latter to form a molecule of salt. These systems, therefore, are not chlorine nor sodium atoms. They are ions and carry negative and positive charges respectively.

MOLECULAR SYSTEMS HAVE THREE CLASSIFICATIONS

Such separation or dissociation of molecules is due not to collision as was the case in ionization of gases but is the result of the attractive influence of neighboring molecules of water. In other words, in the case of a salt solution of this kind, ions are formed spontaneously without the aid of an external electric field. This naturally simplifies the process of conduction materially.

Groups of atoms which will dissociate in this way may be classified under three headings, i. e., as acids, bases or salts. Acids are those systems which always give as one product of the dissociation, positively charged ions which are actually the nuclei of hydrogen atoms, in other words, protons. They are spoken of, ordinarily, as hydrogen ions. Hydrochloric acid, HCl, is an example of this classification, since when it dissociates, the chlorine atom which is normally electronegative, retains the single external electron from the hydrogen atom, leaving of the latter only the nucleus. It may be of interest to point out here, that this is one of the very few instances where the proton will be found to exist alone.

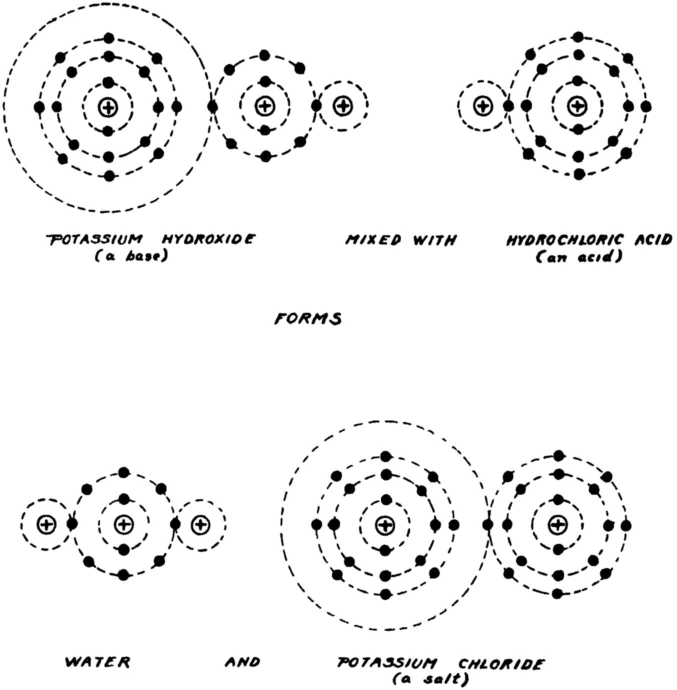


FIG. 25. A SALT IS FORMED BY MIXING AN ACID AND A BASE

Here, potassium hydroxide is mixed with hydrochloric acid. The hydrogen atom of the acid combines with the OH part of the KOH atom, forming water. The potassium atom combines with the chlorine atom to form a molecule of potassium chloride (KCl) which is a salt.

Bases, are those systems which in dissociation, yield negative ions, OH which are formed of one atom of oxygen and one of hydrogen but have retained one external electron from the group with which they were formerly associated. An example is potassium hydroxide, KOH, in which the OH retains the excess electron formerly held by the potassium (K) atom.

The third group of systems which dissociate to produce ions, are the salts which are formed by mixing an acid with a base. When this is done, the positive and negative ions, H and OH, combine to form water, H_2O, as often as they meet and the other ions, when they meet, form molecules of salt. Suppose we mix potassium hydroxide KOH which is a base with hydrochloric acid, HCl. The positive ion, H, of the acid combines with the negative ion, OH, of the base to form water H_2O, while the potassium and chlorine ions combine to form molecules of potassium chloride KCl. In chemical language the reaction is

$$KOH + HCl = H_2O + KCl$$

Thus it is seen that the electron not only governs electrical phenomena but also chemical phenomena. The chemist today explains his reactions in terms developed by the electrophysicist.

THEORY OF ELECTROLYTIC CONDUCTION

It must be evident that this spontaneous production of ions in solutions makes the explanation of conduction in liquids quite simple. If electrically charged plates are introduced into an electrolyte, the ions will be acted upon by the electric field between the plates and will be drawn to the plates. Upon reaching the plates, the negative ions release an electron to the positively charged plate while the positive ions acquire an electron from the negatively charged plate. Thus, they once more become normal atomic structures and in this form either cling to the plate or are released in the form of gas bubbles. We have here the actual transport of atoms or molecules which is characteristic of ionic conduction.

Sometimes, the substance liberated at the plates is not that which is carried through the solution because of certain secondary chemical reactions taking place in the solutions, such secondary reactions being entirely independent of the electrical phenomena.

We have now described the principles underlying the conduction of electricity in gases and in certain classes of liquids. The principles in both instances it will be noted are the same, i. e., electrically charged particles are acted upon by an electric field which cause them to move to the pole of opposite polarity where they serve to neutralize the charge on the plates.

ENERGY RELATIONS

Before taking up the question of conduction in solids in the next chapter we will consider briefly the energy relations involved in gaseous and liquid conduction. When two plates are provided with opposite charges, the electric field resulting represents a certain amount of potential energy. In gaseous conduction, this field acts upon the ions, causing them to move and acquire kinetic energy at the expenditure of the potential energy of the field. When reaching the plate, the kinetic energy of the ions is imparted to the molecular systems of which the plate is made, manifesting itself as heat.

In electrolytic conduction, the dissipation of energy is somewhat different. The energy of the field is spent first in moving the ions against the viscous forces of the liquid which results in heating and second, in detaching or attaching ions at the electrodes in dissociation, and recombination of the electrolyte.

CHAPTER VIII

ELECTRIC CONDUCTION IN SOLIDS

IN AN PREVIOUS chapter,[1] it was shown that the three states of matter are accounted for on the basis of molecular agitation. In gases, the molecules are widely scattered with no cohesive forces acting to keep them together; in liquids, they are spaced more closely with slight cohesive forces acting between them; while in solids, they are spaced so closely and are bound by such powerful cohesive forces that there can be little or no relative motion. What motion there is in solids is vibratory in character rather than translatory as it is in gases and liquids.

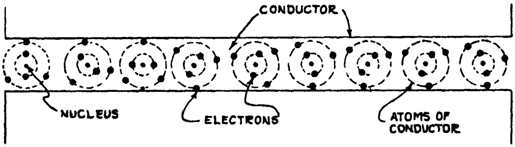


FIG. 26. REPRESENTATION OF ATOMS IN A SOLID CONDUCTOR WHEN NO CURRENT IS FLOWING

The atoms are all normal atoms. Although they are in a state of agitation, each one tends to maintain its normal number of electrons. Occasionally one may be lost in collision but when this happens another electron is acquired from an adjacent atom.

Electric conduction in solids, therefore, must be of a different nature from that in liquids and gases, for there can be no movement of ions through solids nor can there be an unimpeded movement of free electrons as there is in the vacuum tube. Conduction in solids must be explained on a different basis.

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[1] Chapter V, page 38.

SOLID CONDUCTION DUE TO INTERCHANGE OF ELECTRONS BETWEEN ATOMS

Solid conduction, and when we refer to solids here we do so with particular reference to metals, is due to an interchange of electrons between atoms. The atoms of most metals have, in addition to the electrons which form the stable inner orbits, one or more electrons in the extreme outer orbit which are easily removed. These electrons, in fact, are little more than hangers on; if no disturbing forces are present, they remain with the family but will leave home with the slightest encouragement. It is to the wandering proclivities of these electrons that we attribute metallic conduction.

Consider a bar or block of metal. The atoms in it will be spaced close together, so close that they are limited in their movement and are prevented from making any extended excursions from their normal positions. Under these conditions, the external electrons in the outer orbits of adjacent electrons at times will come close together. Occasionally, an electron belonging to one atom will actually come within the sphere of influence of the nucleus of an adjacent atom, thus tending to satisfy simultaneously the demands of the

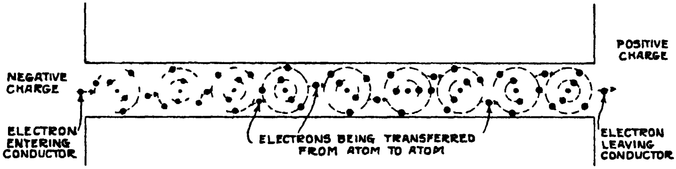
POSITIVE CHARGE
NEGATIVE CHARGE
ELECTRON ENTERING CONDUCTOR
ELECTRONS BEING TRANSFERRED FROM ATOM TO ATOM
ELECTRON LEAVING CONDUCTOR

FIG 27 REPRESENTATION OF ATOMS IN A SOLID CONDUCTOR CARRYING CURRENT

In this case, due to the existence of a difference of potential between the ends of the rod, electrons enter the conductor at the negative end. This gives the atoms at that end an excess of electrons so they transfer one of their own to the next atom. This occurs all along the line, giving rise to an electron "drift" through the rod.

two atoms. When this occurs, one of the atoms will release its hold on one of its electrons, permitting it to wander off to another nearby system which, due to having lost an electron in this manner, needs it. Since the process is duplicated simultaneously in billions of atoms throughout the bar of metal at any instant, there will be billions of these wandering or free electrons in existence. The freedom of these electrons is similar to the freedom of the molecules of a liquid and just as the latter are restrained from leaving the liquid by the attraction of the surface atoms, so are the electrons in a metal restrained from leaving the metal by the attraction of the atoms at the boundary of the metal. Under certain conditions, as we shall see later, some of the electrons may be made actually to leave the metal.

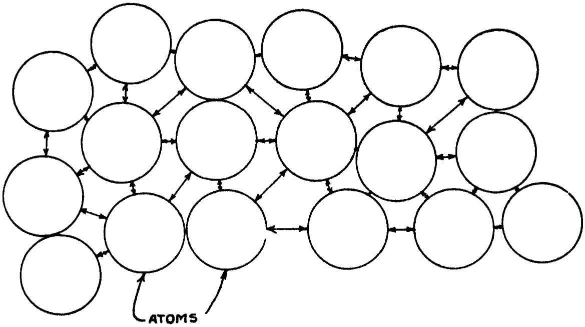

FIG. 28. DIAGRAM ILLUSTRATING WHAT IS MEANT BY THE "MEAN FREE PATH" OF THE ATOM

In any substance, the atoms or molecules are in continual vibration. Each atom is capable of traveling only a short distance before colliding with another. At a particular instant, the length of the lines between the atoms represents the distance which each atom can travel before colliding with another atom. The average of all these distances for all the atoms is the "mean free path" of the atom.

Suppose now that we connect the two ends of the bar of metal we are considering to a source of electric potential so as to establish an electric field through the bar. Not a great deal of imagination is required to see what will happen. The free electrons under the action of the electric field will at once be drawn in the direction of the positive terminal of the bar although their progress will be impeded by countless billions of atoms in their path. There will be innumerable boundings back and forth and a single electron will undergo innumerable "captures" and "releases" but if the sum total of all the free electrons is considered, there will be superimposed upon the haphazard motions of the electrons, a directed motion along the lines of force constituting the field toward the positive end of the rod. There will be a "drift" of electrons towards the positive end. This "drift" of electrons constitutes what we know as an electric current. It will be well to remember this fact, that electrons in motion constitute an electric current.

SPEED OF ELECTRON DRIFT

Now the value of the electric charge represented by a single electron is exceedingly small and to produce a current of appreciable strength, the motion of billions of electrons is necessary. To make a current of even one ampere, it is necessary that 10^{19} (ten million, million, million) electrons pass by a given point in one second. If a counting machine were constructed which would count this number of electrons at the rate of one million per second, the machine would have to be operated continuously, day and night, for over 317,000 years.

Despite this enormous number, the progressive movement of electrons in a metallic conductor is exceedingly slow. If we accept the assumption that there are as many free electrons in a piece of copper wire as there are atoms, to produce a current of one ampere in a copper wire one millimeter in diameter requires that the average velocity of the electrons be only about 0.001 cm. per sec.[2]

Note that we say *average* speed. The velocity of the individual electrons is very high. Even when no current is flowing in a wire, the electrons have a haphazard motion due to thermal agitation of the atoms of about 35 mi. per sec. The average velocity under these conditions is, of course, zero; there are just as many electrons moving one way as another.

SLOW AVERAGE SPEED OF ELECTRONS DUE TO COLLISIONS

The reason for the extremely slow progressive movement of electrons in a wire or rod is to be found in the tremendous number of collisions they have with the molecules and atoms composing the metal. Electrons moving toward the positive end of the conductor cannot travel far before colliding with atoms or molecules. Since the atoms and molecules are many thousands of times more massive than the electrons, the latter rebound from the atoms with practically the same velocity as that with which they approached the atoms. Naturally, at any instant there are almost as many electrons moving in a negative direction as there are in a positive direction.

If it were not for the innumerable collisions experienced, an electron in a metallic conductor would gain a tremendous velocity in an extremely short interval of time, since only a small potential gradient is required to accelerate an electron rapidly. But the mean free path between successive collisions is small and because of this the velocity acquired by an electron due to the potential gradient is extremely small. As the potential difference between the ends of the conductor is increased, the average velocity toward the positive end increases but slightly. With a current so large that the copper wire is heated to the melting point, the drift of electrons is less than 1 cm. per sec.

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[2] Morecroft, Principles of Radio Communication, page 11.

As long as a difference of potential is maintained between the ends of the conductor, there will be a drift of electrons toward the positive end. If the ends of a copper rod are connected to the poles of an electric battery as shown in Fig. 29 the electrons move slowly towards the end P. When they arrive at P, they leave the rod and travel down the wire to the positive pole of the battery, through the battery to the negative pole, through the other connecting wire and back to the rod. As fast as the electrons leave the end P, they are supplied at the end N. The cause of the flow is, of course, the battery, which, by virtue of the chemical action within the cells, maintains the ends of the rod at a constant difference of electric potential or pressure. The action would be the same if the difference of electric pressure was produced by any other means, say by a dynamo, or by an old-time frictional machine. A battery or generator, therefore, is virtually a pump for pumping electrons through the system.

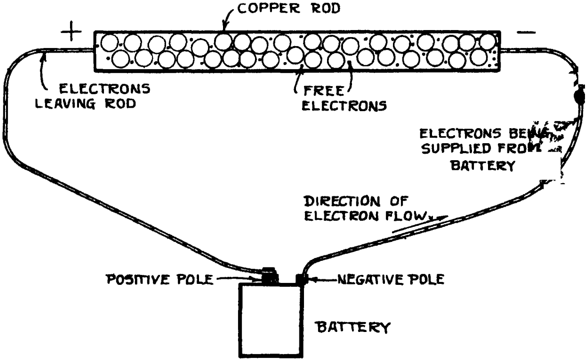

FIG 29. ELECTRIC CURRENT CAUSED BY THE "DRIFT" OF ELECTRONS THROUGH A METAL ROD

JOHN MILL'S ANALOGY

Various analogies have been resorted to for explaining metallic conduction and while all of them are helpful in obtaining an understanding of the phenomena, none in the author's opinion is more ingenious than the one given by John Mill.[3] Mr. Mill pictures a metallic conductor as an enormous basket ball court on which there are disposed a large number of players. Each is assigned to a relatively small circular space within which he is free to move. The space may, however, overlap into the space occupied by one of his neighbors so that even within his one area of action a player's movements are sometimes restricted by the necessity of avoiding a collision with his neighbor.

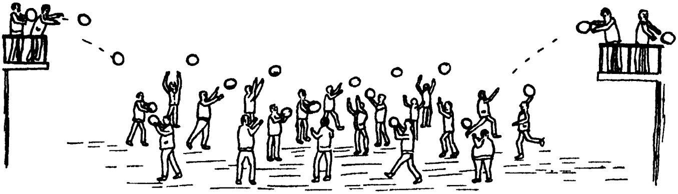

FIG 30. CONDUCTION IN SOLIDS MAY BE LIKENED TO THE ACTION OF A GROUP OF PLAYERS ON A BASKET-BALL COURT

The players are the atoms and the balls the electrons As additional balls are tossed into the court at one end, there is a progressive movement of balls to the opposite end where they are expelled from the court.

Suppose, now, that a large number of balls is tossed to these players so that each player has a ball, and let them begin to toss the balls to each other. The balls correspond to the wandering electrons and the players to the atoms. If a player with a ball in his hand finds another ball being tossed to him, he will find difficulty in holding both of them, so he tosses the one he has in his possession to some other player in order to make room for the one he has just received or will receive. At any instant, a number of balls will be in the air but none of them ever leave the court.

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[3] Within the Atom.

If, now, at one end of the court we toss into it a certain number of additional balls and at the opposite end remove a similar number, it will be obvious that the players at the receiving end will not be able to handle all of the balls and there will be a general movement of balls to the end of the court where there is a deficiency. This general movement of the balls towards the exit end will be superimposed upon the haphazard motion which existed before the influx of new balls.

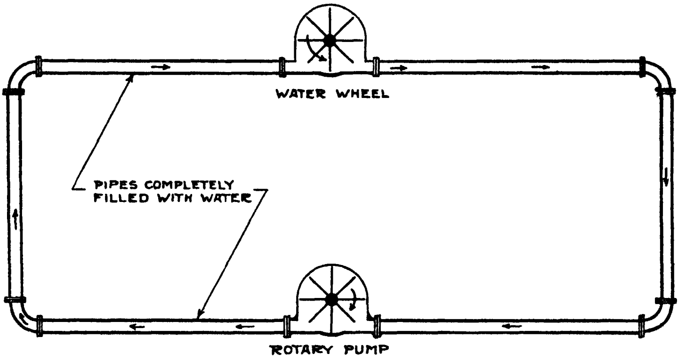

FIG. 31. HYDRAULIC EQUIVALENT OF AN ELECTRICAL CIRCUIT TO ILLUSTRATE THE SPEED OF PROPAGATION OF AN ELECTRIC CURRENT

When the pump is started, the water wheel begins to turn almost immediately, although the water from the pump may not reach the water wheel for a long time afterwards.

The introduction and withdrawal of additional balls in this manner is analogous to impressing a difference of electric potential across opposite ends of a metallic conductor. The greater the number of balls introduced per second the faster will be the progressive movement of balls down the length of the court, but at no time will the speed of this progressive movement be comparable in magnitude to the speeds of the individual balls as they are thrown from one player to another.

Metallic conduction, it will be evident, is pure electronic conduction—that is, it is characterized by the absence of transport of matter. In a previous paragraph, the battery or generator in an electric conducting system was likened to a pump. While this analogy is helpful, it must not be carried too far, for there is no transport of matter in the electrical circuit as there is in the hydraulic system. In metallic conduction, the electrons are handed from one atom to another but the atoms do not move.

PROPAGATION OF THE EFFECT

The slow progressive motion of the electrons in a metallic conductor may seem incompatible with the speed at which electricity travels through a conductor which, as everybody knows, is extremely rapid. A moment's reflection, however, should make apparent that what is involved here is not the velocity of electrons but the propagation of the effect. In Fig. 31 is depicted a closed pipe line filled with water and containing in one side a rotary pump and in the opposite side a water wheel. It is obvious that when the pump is turned the water wheel will begin to turn almost at the same time, although the transmission of water from the pump to the water wheel may take several minutes or even hours depending upon the length of the system. A similar relation holds in the electric circuit between the progressive motion of the electrons and the velocity of propagation of the effect of the current.

Thus we have built up a theory of electric conduction which is based upon the atomic structure of solids and which is capable of explaining many observed phenomena in electric circuits. It must be understood, however, that this is only a theory and, as is always the case with a theory, is open to criticism. Indeed, this theory at the present time is under fire because certain mathematical equations[4] which result from it are not entirely satisfactory; however, it is one of the most satisfactory theories of metallic conduction so far developed and at least enables us to picture what is going on inside of a wire carrying current.

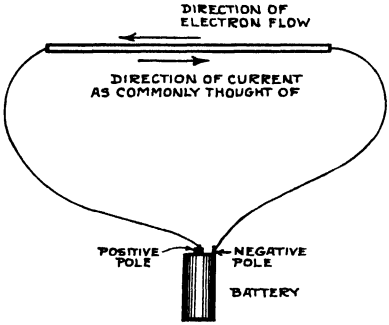

FIG. 32. THE DIRECTION OF THE FLOW OF ELECTRONS IS JUST OPPOSITE TO THAT IN WHICH WE ORDINARILY BELIEVE THE CURRENT IS FLOWING

One thing in these explanations of electronic conduction must be directed to the reader's attention though he may have noticed it; that is in regard to the direction of the movement of electrons through the conductor, which is always from the negative to the positive terminal. This is contrary to our usual conception that electricity flows from positive to negative. The discrepancy is due to the fact that the pioneer electrical experimenters, having no real understanding of the nature of electricity in the sense that we know it today, arbitrarily assumed the direction of current to be from positive to negative. In view of the facts disclosed by the electron theory, this assumption is now known to be contrary to actual facts and while it has made little difference in practical electrical engineering, it now causes considerable misunderstanding in the mind of the student not duly informed. It is an unfortunate condition and because of it we must accustom ourselves to saying one thing and thinking another. When we talk of current flowing from the positive to the negative terminal of a battery or generator, we must think of the electrons (which constitute the current) as moving from the negative to the positive. So we must suffer for the mistakes of our fathers in science.

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[4] Matter, Electricity, Energy, by Gerlach and Fuchs, page 146.

CHAPTER IX

RELATION OF ATOMIC STRUCTURE TO CONDUCTION

THERE IS A prevailing belief that science is cold—devoid of romance and religious feelings and that the scientist is an unemotional being, scarcely to be classified as human. This belief is due in a measure, no doubt, to the fact that the scientist has always kept to himself, first by necessity, later by choice. The first men of science were regarded as little more than emissaries of the devil and it was worth their very lives to venture out of their laboratories. Naturally they kept to themselves and as they had no end of things to interest them, the populace were the losers. But the scientist acquired the reputation of being cold and devoid of religious feeling.

That this reputation is unjust must be evident to anybody who has ever set a foot inside of a scientific laboratory or who is at least familiar with the work of scientists. The scientist is perhaps more sincerely religious than many of his critics; his religion may be a different kind and not open to display but if a sincere appreciation of the universe in which we live—of its beauties, its truth, its harmony, is not religion, then nothing is.

ROMANCE IN SCIENCE

As for romance, it lurks at the bottom of every test tube. It is to be found in the eyepiece of every telescope and microscope, in the evacuated space of every vacuum tube. Where is there greater romance than that which is the astronomer's when his spectroscope unfolds a tiny pencil of light from a star a thousand light years away and discloses the nature of the elements on that star with as much certainty as the chemist analyzes a sample in a test tube?

So, in the pursuit and study of the electron, romance is ever present. Who, contemplating a block of metal, could have imagined that its impenetrable mass consists almost entirely of space—that what matter there is, is in unceasing motion and that the small particles within the boundaries of its surfaces have been whirling about at incredible speeds since the beginning of time?

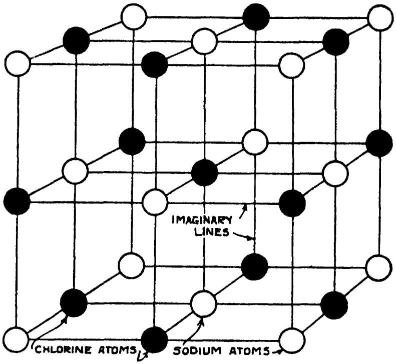


FIG. 33. CUBIC CRYSTAL STRUCTURE OF SODIUM CHLORIDE

This structure is typical of many substances. If the crystal is that of common salt, the black circles represent the sodium atoms and the light circles the chlorine atoms.

ELECTRON AT THE ROOT OF ALL PHENOMENA

The electron, we have seen, is at the root of all phenomena; it governs the characteristics of all elements and is the basis of all chemical activity; therefore it is at the basis of life itself. There can be little doubt but that all biological phenomena are explainable in terms of the electron.

Seemingly tiny particles, endowed with incredible amounts of energy moving in accordance with inviolable law, they form the building blocks of the universe.

What they are, outside of the fact that they represent the ultimate electrical charge, we do not know. Sometimes behaving as waves, at other times as particles, always giving rise to wave phenomena, they harbor the ultimate secret of the universe. In gases, in solids, in liquids, they always seem the same; the electron from one substance is the same as from another. They are everything and explain everything.

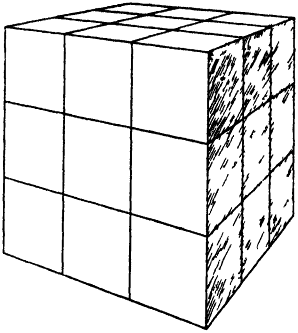
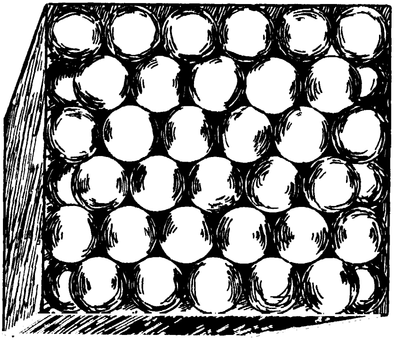


FIG 34 BY ARRANGING CUBES IN REGULAR ORDER AND IN LAYERS, THEY CAN BE MADE TO FILL THE CONTAINER ENTIRELY

In these articles, we have barely touched upon the multitudinous activities of the electron. We have described how they effect conduction in gases by ionizing normal atoms, how in liquids they govern chemical action and production of ions, and how in solids they effect conduction by jumping from atom to atom. Later we shall see how they are responsible for the production of light and x-rays, how they give rise to radioactive phenomena and many other things. First, however, we shall discuss the part they play in governing resistance in solids and in determining whether a solid is a conductor or an insulator.

EFFECTIVENESS OF CONDUCTION DEPENDENT UPON SPACING OF ATOMS

In the preceding chapter, conduction in solids was compared to the action of a large number of players on a basketball court in tossing balls around. In considering this analogy, it must be evident that the effectiveness of conduction of balls is dependent to a certain extent upon the amount of space between the players and upon their relative motion with respect to each other.



35 SPHERES WILL FILL ONLY A PORTION OF THE TOTAL VOLUME OF A CONTAINER

If the players are close together and remain stationary, the balls will be passed from one end of the court to the other with the least effort and with the least commotion. If, however, they should become excited and jump around a great deal (keeping within their assigned radius of action), thereby suffering many collisions among themselves, or if they should spread out so as to make it necessary to throw the balls farther, conduction would become less effective.

VARIATION OF RESISTANCE WITH TEMPERATURE

This is exactly what happens in a solid conductor when the temperature is raised. As has been shown[1], even at ordinary temperatures the atoms of a solid are in incessant vibration. As the temperature is raised, more kinetic energy is imparted to the atoms and this vibration becomes more violent, thereby lengthening the mean free path between collisions. Under these conditions, as in the case of the basketball players, more energy is required to shoot an electron from one atom to another, making it more difficult to pass a given number of electrons in a given time. Thus we say that the resistance of the metal has increased with the temperature, a fact which has long been known to the electrical men from everyday experience. Most substances undergo an increase in electrical resistance as the temperature rises.

Naturally, the converse is equally true; as a metal is cooled, the kinetic energy of the atoms becomes less and the amplitude of vibration decreases. The atoms require less space and the metal contracts. In this condition, the passage of electrons is greatly facilitated, since the external orbits of the atoms tend more and more to overlap, thereby neutralizing the forces acting on the electrons in those orbits. For each degree that a metal is cooled, therefore, the resistance decreases a certain definite percentage. This would indicate that at an extremely low temperature (near absolute zero) the resistance of a conductor would become extremely low, and this has proved to be the case. We shall discuss this aspect of conduction more fully later but here, it will be sufficient to state that at the temperature of liquid helium, certain metals become perfect conductors.

Resistance in solid conductors is due to the fact that the electrons must travel gaps between atomic systems. Within the sphere of influence of an atom the electron is believed to move freely. According to this theory, when the atoms no longer dash to and fro they may be so close that an electron passes from one to the next without essentially crossing any gap.

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[1] Page 39.

So far, our theory of electric conduction in metals has served us well but now, how shall we explain the fact that certain substances, usually relatively poor conductors, decrease in resistance with an increase in temperature? Carbon is such a substance. When the old style carbon filament lamp was cold, its resistance was high but shortly after the current was turned on, and the filament heated to incandescence, the resistance fell to a low value.

EFFECT OF CRYSTAL STRUCTURE

In this case, probably, the arrangement of atoms or molecules in the material is such that the atoms are not permitted normally to approach each other closer than a certain distance. This may be due to the peculiar geometrical arrangement of the atoms which in turn is the

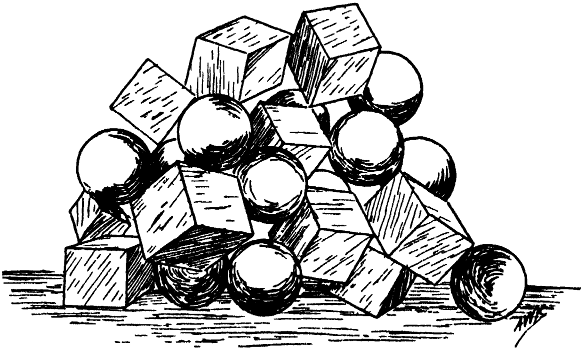

FIG. 36. A SIMILAR CONDITION PREVAILS IF THE OBJECTS ARE OF MIXED SHAPE, SOME SPHERICAL AND SOME CUBICAL

result of the configuration of electrons in the atom. While it is unreasonable to talk of the shape of an atom, it is reasonable to suppose that, because of the configuration of the electrons, the atoms would behave like solid objects of definite geometrical shape.

Suppose we consider a box full of small cubes—cubes of sugar, for instance. If care is taken, these cubes can easily be piled in rows so as completely to fill the space in the box. If the sugar was in the form of small spheres instead of cubes, however, they could not be made to fill all the space in the box. A similar condition would prevail if the lumps of sugar were of mixed shape—some spherical, some cubical, some other shapes. It is also apparent that while, in the case of the cubes, all surfaces of all cubes would be in actual contact, in the case of spheres only a small portion of the total area of the spheres would be in actual contact.

EXPLANATION OF NEGATIVE TEMPERATURE COEFFICIENT

Now, a similar condition prevails in the atomic structure of crystals. By means of x-rays, as will be discussed in later articles, scientists have been able to determine the geometrical arrangement of the atoms in various materials. Of course, since atoms are not solid bodies but merely systems of electrons and protons, there can be no such thing as "contact" between atoms as there is between cubes of sugar. The forces (repelling and attracting) in the atom are such, however, that the atoms are compelled to take certain positions with respect to each other. Thus, in the case of a sodium chloride crystal, the atoms of sodium and chlorine are arranged in a simple "cubic" fashion. The black balls represent the sodium atoms, the light ones the chlorine atoms.

This brief discussion of crystal structure will enable us better to understand why such substances as carbon decrease in electrical resistance as the temperature increases. At normal temperature, the arrangement of the atoms in these substances is such that they are relatively far apart and the forces holding the electrons are sufficiently great so that no ordinary electric field will remove them. Only occasionally will an electron belonging to one atom come close to the sphere of influence of another atom and then under the action of an external electric field, this electron may be passed from its own atom to the next. Naturally, at ordinary temperatures such materials are poor conductors.

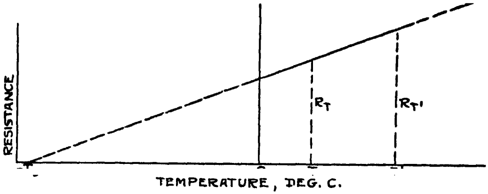

FIG. 37. CURVE SHOWING THE VARIATION OF RESISTANCE WITH TEMPERATURE

The relation of resistance of conductors to temperature is substantially linear, as shown. If this linear relation were maintained for all points of the temperature scale, at T_0 the resistance would be zero. At extremely low temperatures, this linear relation does not hold, however.

As the temperature is increased, however, the molecular agitation among the atoms becomes more violent so that the collisions become more frequent. Also, because of the increased kinetic energy, the electrons are not held to the atom as tightly as before and they are loosened more easily. Thus, the conductivity of the material increases. The higher the temperature, the more violent and frequent the collisions and the more often is an electron passed from one atom to another—a hand to hand exchange. In the jargon of everyday electrical engineering, such substances are said to have a negative temperature coefficient.

TWO MAIN FACTORS CONTROL RESISTANCE CHARACTERISTICS

From the foregoing, it must be apparent that two main factors control the resistance characteristics of solid conductors, first, the geometrical arrangement of the atoms and the distance between them; second, the degree of tightness with which the electrons are held to the atom. The latter varies with different atoms as we have seen.[2]

To free an electron from an atom requires a certain definite amount of energy, depending upon the stability characteristics of the atom. In some cases, a potential gradient of a few volts is sufficient, in others, a considerably greater potential is necessary. With a given spacing and arrangement of atoms, the resistance of the substance is dependent upon the amount of energy required to free the electrons. The atomic arrangement, however, is quite as important a factor and it is only when the two factors are considered together that a satisfactory theory of solid conduction can be constructed.

Any conductor is heated by an electric current. As electrons under the action of an electric field are carried along, the energy of the field is imparted to the electrons as kinetic energy. As these electrons collide with the atoms and other electrons, this energy manifests itself in a general increase in the molecular agitation of the body. This we know and recognize as heat.

As the conductor heats, the resistance is either increased or decreased, depending upon whether the temperature coefficient is positive or negative. The energy for producing this heating effect is obtained from the energy stored in the electric field.

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[2] Chapter IV, Page 30.

CHAPTER X

DIFFERENCE BETWEEN INSULATORS AND CONDUCTORS

SO FAR, in this study of electricity, we have concerned ourselves mainly with the reasons for electrical conduction in various materials. In this chapter we are going to try to learn something about insulators. What is an insulator? What is the difference between an insulator and a conductor?

In the preceding chapter, we learned that the electrical resistance of a solid conductor is dependent upon two things; the arrangement of the atoms and the degree of tightness with which the electrons are bound to the atom.

It must be evident that if the distance between atoms is relatively great and if the electrons are bound to the atom so tightly that no ordinary potential gradient can loosen any of them, no current can flow. Substances in which this state of affairs prevails are known as insulators.

Naturally, there is no sharp dividing line between substances which may be classified as insulators and those which may be classified as conductors. Whether a substance is to be classified as an insulator or a conductor depends largely upon the purposes for which it is to be used. Insulators are really high resistance conductors with very high negative temperature coefficients.

Furthermore, a substance will not always remain an insulator for, as the electric potential across an insulator is gradually increased, it is reasonable to suppose that finally a value of potential will be reached where the force tending to release an electron from an atom will overcome the attractive force of the nucleus and the electron will be freed. This is the point at which we say an insulator breaks down. Even such fine insulators as glass, mica and porcelain break down if the potential is high enough. This action will be discussed in greater detail in a subsequent paragraph.

Below the breakdown potential, insulators are incapable of conducting current, but when placed in an electric field, certain changes take place within the atoms which are extremely interesting. When an insulator is placed in an electric field, the atoms considered as complete units will not be affected. Being electrically neutral, they will not be urged one way or another. This, however, is not true of their component parts, the nuclei and the electrons, for under the action of the field the electrons tend to move in one direction and the nuclei in an opposite direction. The movement of these elements is limited by the forces inherent in the atom itself so the effect of the field is a shift of the electron ring or orbit with respect to the positive nucleus. The magnitude of this shift or displacement will be such that the internal forces of the atom tending to keep the positive charge and the electron orbits centered with respect to each other, will exactly balance the force of the field on it due to the external charge.

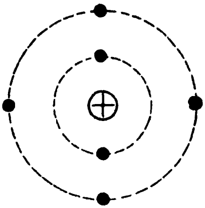

FIG. 38. HYPOTHETICAL ATOM OF AN INSULATING MEDIUM NOT IN AN ELECTRIC FIELD

This is illustrated in Figs. 38 and 39, which show a hypothetical atom. When no electric field is present, the electrons are arranged around the nucleus in the normal manner as shown in Fig. 38. Under the influence of the electric field, however, the nucleus which is positively charged tends to move toward the negative pole producing the field while the orbital electrons tend to move toward the positive pole. This results in a distortion of the electronic orbits as well as a displacement of the nucleus from its central position, as shown in Fig. 39. For an instant, there is an actual movement of these elements but this ceases when the attractive force of the nucleus, tending to pull the electrons back to their normal configuration, is exactly balanced by the opposing force of the external field. The effect of an electric field on an insulating medium is thus to produce a displacement or distortion of the atomic structure which is proportional to the field intensity.

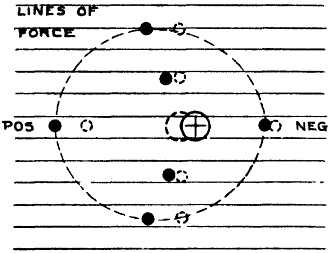

FIG. 39. ATOM OF INSULATING MATERIAL SHOWN IN FIG 38 IN AN ELECTRIC FIELD

Due to the action of the field, the nucleus tends to move toward the negative pole while the orbital electrons tend to move toward the positive pole. They are restrained from leaving the atom, however, due to the internal forces. This results in the atom being distorted.

In attempting to visualize the manner in which an atom is distorted under the influence of an electric field it must be understood that the electrons are in motion. When we refer here to a displacement of the electrons, what is really meant is a distortion of the orbits in which the electrons move.

POTENTIAL ENERGY OF FIELD ABSORBED BY DISTORTED ATOM

This distortion, requiring for its establishment a certain amount of work on the part of the field, results in an absorption of a corresponding amount of energy which is a portion of the potential energy of the field. The amount of potential energy thus stored in the atoms of the insulating medium depends upon the value of the charge producing the field, on the internal atomic forces limiting the displacement of the atomic structure, and in the number of atoms per unit volume of the insulator. It thus depends upon the nature of the insulator commonly termed the dielectric.

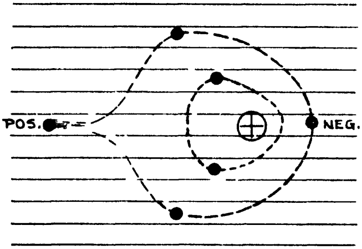

FIG. 40. WHAT HAPPENS TO AN ATOM OF INSULATING MATERIAL IN AN INTENSE ELECTRIC FIELD

As the field strength increases, a value is reached finally where the force due to the field overcomes the attraction of the nucleus for one of the external electrons, which results in the latter being torn away.

DIELECTRIC CONSTANT

In Chapter V[1], it was shown that the production of an electric field was accompanied by a storage of potential energy in the field. Now, we find that when an insulating medium is placed in this field, part of the potential energy originally stored in the field is used in effecting the atomic distortion of the medium. Thus, the amount of energy remaining in the field is decreased by an amount represented by the ratio 1/k, which is evidently dependent upon the nature of the insulating material.

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[1] Page 45.

In order to restore the potential energy in the field to the value it would have in the absence of the insulating material, it is necessary, therefore, to increase the value of the charge producing the field from a value of e to a value of e′ such that

$$e \div e' = k$$

The value k, which is characteristic of the dielectric material, is called the dielectric constant of the material. Its value varies for different materials, being approximately 1.00059 for air, 2.23 for turpentine, 5.6 to 6.6 for mica, 8 for glass and 80 for water.

Before we wandered off to this discussion of the meaning of the term dielectric constant, we left the atoms of our insulating material in a state of distortion or strain. Let us see whether we can't get them back in shape again.

THEORY OF INSULATION BREAKDOWN

As long as the electric field remains, the atoms remain distorted. If the field strength decreases, the forces in the atom pull the electrons back to their normal positions. Suppose, however, that the field strength is increased; then, what will happen?

Simply this: as the field strength gradually increases, finally, a value is reached such that the force tending to distort the atom overcomes the force of the nucleus tending to keep the outermost electrons in place, and the outer electrons "let go" so to speak. This occurs in only a few atoms perhaps—those in which the bond between the electron and the nucleus is weakest.

As these liberated electrons start to move through the insulator, they collide with other atomic systems and since these are all in a state of severe strain, they in turn part with their outermost electrons. In a short time, the cumulative effect of this action results in a complete disintegration of the insulator at the point of

DIELECTRIC CONSTANTS FOR VARIOUS SUBSTANCES

Substances	Values of dielectric constant
Air	1.0
Glass	4 to 10
Mica	5.6 to 6.6
Hard rubber	2 to 4
Paraffin	2 to 3
Paper, dry	1.5 to 3.0
Paper (treated as used in cables)	2.5 to 4.0
Porcelain, unglazed	5 to 7
Sulphur	3.0 to 4.2
Marble	9 to 12
Shellac	3.0 to 3.7
Beeswax	3.2
Silk	4.6
Celluloid	7 to 10
Wood, maple, dry	3.0 to 4.5
Wood, oak, dry	3.0 to 6.0
Molded insulating material, shellac base	4 to 7
Molded insulating material, phenolic base ("bakelite")	5.0 to 7.5
Vulcanized fibre	5 to 8
Castor oil	4.7
Transformer oil	2.5
Water, distilled	81.0
Cottonseed oil	3.1

breakdown. This explains why a good insulator such as glass or mica will retain its high insulating qualities up to the very moment of breakdown.

This theory of insulator failure is only one of many and in practice is the least serious, since it is governed entirely by the value of the electric field. Many other things affect insulator behavior, such as temperature, presence of gas within the dielectric, moisture, conducting particles and none of these are as easily controlled as is the field strength. The theory of insulator breakdown is an extremely important one in electrical engineering and it has received a great deal of discussion. Only the most fundamental aspect of this subject will receive consideration here.

OTHER FACTORS AFFECTING PERFORMANCE OF INSULATORS

Among the various factors which affect the performance of insulators, an important one is temperature. As the temperature of the dielectric is raised, the atoms and molecules undergo increased agitation with the result that collisions become more frequent and violent. These collisions contribute to the weakening of the bond between the electrons and their respective nuclei and if at the same time the insulator is heated, the electric field is applied, the combination of forces tending to liberate the electrons will finally result in a partial breakdown of the insulator in the manner already described. Generally such a partial breakdown due to heating is followed rapidly by the complete breakdown of the insulator.

Many substances which at ordinary temperatures are good insulators, at very high temperatures become fairly good conductors. Glass, for instance, is a most excellent insulator at normal temperatures, yet if it is heated to red heat by an external source, it becomes a fairly good conductor and if the potential applied is sufficiently high, enough current will pass through it to melt it. Molten glass thus becomes a good conductor.

Another factor affecting the performance of insulating material is the homogeneity of its structure. It is evident that if the material contains any minute voids in which gases might collect, these gas pockets may, under favorable circumstances, become the seat of gaseous ionization. Such ionization would result in heating with a consequent lowering of the insulating properties of the material.

Thus the electron not only explains the difference between conductors and insulators but also gives us the reason why insulators do not remain insulators. Before we leave this subject of insulators, we shall discuss more fully in the next chapter, the peculiar storage of energy in the distorted atoms of insulators. This has an important application in electrical engineering, in the static condenser or capacitor. After we have considered the theory and action of the condenser, further aspects of the electron in conducting materials will be considered.

CHAPTER XI

THEORY OF THE CONDENSER

ALTHOUGH the matter was passed over briefly, the storage of energy in the distorted atoms of an insulating medium, described in the preceding chapter, is an extremely interesting phenomenon and one which, in the device known as the static condenser or capacitor, has proved of inestimable value. In this chapter, therefore, we shall discuss more fully the principles which underly condenser operation.

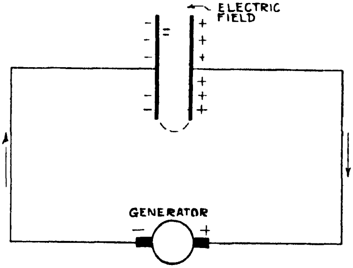

FIG. 41. CONDENSER IN CIRCUIT WITH A GENERATOR
Due to the difference of potential across the generator, electrons are removed from the positive plate of the condenser and a like number deposited on the negative plate. This causes a momentary current to flow in the direction indicated by arrows.

A condenser consists essentially of two parallel plates separated by an insulating medium which may take the form of either a solid, liquid or gas. When the plates of such a condenser are connected by means of a metallic conductor to a battery, generator or any other source of electric potential, as shown in Fig. 41, a certain difference of potential will be established between the two plates. Because of the electromotive force developed by the generator, a certain number of electrons will be removed from the positive plate and a like number deposited on the negative plate, the transfer from one plate to the other being effected through the metallic circuit in which the generator is connected. During the time that this transfer of electrons is being effected, an electric current flows in the metallic circuit.

Thus, the plates become "charged" with electricity of opposite polarities—the plate carrying the excess of electrons acquiring a negative charge while the one from which they are removed, a positive charge. Furthermore, an electric field will be established between the plates, which acts in opposition to the electromotive force of the generator.

WHY THE ACTION OF THE FIELD IS OPPOSITE TO THE ACTION OF GENERATOR

A few words of explanation may make this fact more clear. In Chapter VI[1], it was shown that when opposite charges of electricity are separated, work is done against the attractive influence due to the electric field, and if the force tending to separate the charges is suddenly removed, they will be drawn together again by virtue of the potential energy stored in the field. As stated in that article, however, it does not matter which way the neutralization of the charges is effected—whether the plates on which the charges reside are permitted actually to come together or whether the excess electrons on the negative plate are permitted to return to the positive plate through a conductor, the same purpose will be served. It is obvious, then, that if the two charged plates were suddenly connected by a metallic conductor, a flow of electrons would take place from the negative to positive plate.

If the diagram of the condenser and generator circuit shown in Fig. 41 is now examined it will be found that such a metallic circuit between the two plates exists in the generator circuit itself. If the generator were short circuited as shown in Fig. 42, a sudden flow of electrons would take place in a direction just opposite to that in which the generator sent the electrons in charging the plates. Thus, it is obvious that the action of the field between the plates is in direct opposition to the action of the generator.

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[1] Page 49.

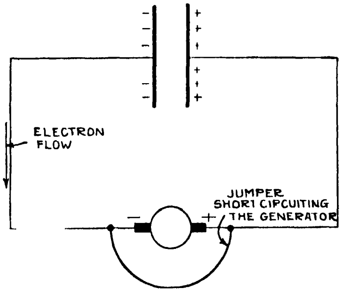

FIG. 42. DISCHARGING THE CONDENSER BY PLACING A JUMPER ACROSS THE GENERATOR

By short circuiting the generator, the electromotive force of the generator is removed from across the condenser, and the latter discharges producing a current in the direction indicated.

CAPACITY OF A CONDENSER

This fact being understood, it may be seen that when the electric field between the plates becomes equal in value to the difference of potential across the generator, the transfer of electrons from the positive to negative plates ceases and the condenser will be charged. From Coulomb's law,[2] it can be shown that for a given condenser, the value of the field between the plates is directly proportional to the value of the charges on the plates; therefore, also, that the charge of a condenser is directly proportional to the difference of potential between the plates, this being the measure of the field. The ratio e/v of the charge of a condenser, e to the potential difference v, between its plates has, therefore, a constant value C for a given condenser. This value C is called the capacitance or electrostatic capacity of the condenser. In the practical system of units, the unit of capacitance is the farad, which is the capacitance of a condenser which requires a difference of one volt between its plates to store a charge of one columb. In terms of electrons, a columb equals 6.3 10^{18} units.

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[2] Page 55.

CHARGING CURRENT

The current of electricity along the metallic circuit which has been shown to take place while the condenser was being charged is called the charging current of the condenser. If the condenser plates were contained in a perfect vacuum, this charging current would be the only displacement of electricity taking place in the system during the time of charging, but condenser plates are rarely in vacuum and usually have some insulating material between the plates, which causes an additional displacement of electricity, as will now be described.

In our study of the action of insulating material in an electric field in the preceding article, we learned that the atoms of insulating materials are distorted when an electric field is applied. The energy necessary to produce this distortion was shown to be derived from the potential energy of the field itself.

DISPLACEMENT CURRENT

Assuming now that the condenser in Fig. 41 has no dielectric material of any kind between its plates and that it has been charged to a certain potential by the generator, let an insulating medium be inserted between the plates. Under the action of the field, the atoms of this insulating medium will undergo distortion with a consequent absorption of potential energy from the field. This results in a lowering of the potential on the plates, so that in order to maintain it at its previous value, additional electrons will have to be supplied to the negative plate, giving rise to an additional current. This current is known as the displacement current.

From this, it follows that the capacity of a condenser is dependent to a certain extent upon the medium between the plates, that is, upon the dielectric constant k, of the medium. If a charge e is required to produce a field f in vacuum, a charge k e will be required to produce the same field in an insulating medium of dielectric constant, k. If then $C = e \div v$ is the capacitance of a condenser in vacuum, the capacitance of the same condenser in an insulating medium of dielectric constant k, will be

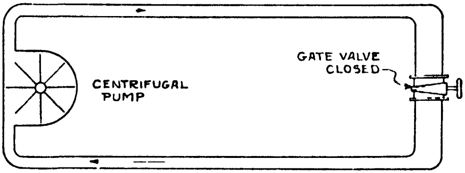

FIG. 43. HYDRAULIC ANALOGY TO SHOW THE SIGNIFICANCE OF CHARGING CURRENT IN A CONDENSER IN VACUUM

When centrifugal pump is started pressure builds up in upper leg until the back pressure just balances the pump pressure. The momentary current which results is due to the compressibility of the water.

$$C^1 = \frac{k\ e}{v} = k\ C$$

where C^1 is the capacity of the new condenser.

Thus, we have here a simple method of determining the dielectric constant of any insulating material by first measuring the capacitance of the condenser in vacuum and then of the same condenser using as a dielectric the material under test. The ratio of the latter to the former gives the dielectric constant k.

HYDRAULIC ANALOGY

In forming a conception of the action taking place in charging a condenser, the two causes of the charging current must be definitely understood. The charging current of a condenser in vacuum is due to the compressibility of the electrons in the metallic conductor of which the circuit is composed. When a dielectric other than vacuum is used, however, in addition to the current due to the compressibility of the electrons in the metallic conductor, there is also a current due to the distortion of the atoms in the dielectric.

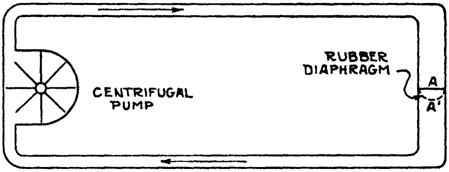

FIG. 44. HYDRAULIC SYSTEM EQUIVALENT TO AN ELECTRIC CIRCUIT HAVING A CONDENSER WITH MATERIAL DIELECTRIC

In this case, the closed valve of Fig. 43 is replaced by a flexible diaphragm. Under the pressure of the pump the diaphragm is distended, resutling in a much larger charging current than was the case in Fig. 43

A simple hydraulic analogy may make this very clear. In Fig. 43 there is shown a centrifugal pump connected into a rectangular system of pipes having a gate valve in the leg opposite the pump. The pump corresponds to a direct current generator. If the gate valve is closed, assuming the entire system to be filled with water, and the pump started, a pressure will be built up in the upper half of the system. For a brief instant, a current will be established but as soon as the back pressure equals the pressure of the pump, this current will cease, even though the pump is maintained in operation. This momentary current is due to the slight compressibility of the water and corresponds to the charging current of an electric condenser in vacuum.

Suppose, now, that the valve is replaced by a flexible diaphragm of rubber, as in Fig. 44. Under these conditions, when the pump is started, the pressure will distort the diaphragm from a position A to a position A^1 and a considerably greater current will flow. When the diaphragm has reached a position A^1, the elastic force of the material will just balance the pressure due to the pump and the current will cease. Thus, in a circuit of this kind, we have in addition to the current due to the compressibility of the water, a current due to the distortion of the diaphragm. This corresponds to the distortion of the atoms in the dielectric of an electric condenser.

In the hydraulic circuit, the charging current would be a function of the elasticity of the diaphragm, just as in the electrical circuit, it is a function of the dielectric constant. Capacity in an electrical circuit, therefore, is analogous to elasticity in an hydraulic or mechanical system.

CHAPTER XII

PRODUCTION OF THE MAGNETIC FIELD

IT IS SOMEWHAT of an anomaly that today, in view of our great advances in scientific knowledge, we are less able to explain the absolute nature of the "electric field" than we were twenty-five years ago. This is due in a great measure to the baffling mystery of space.

Twenty-five years ago, most scientists were pretty well reconciled to the idea of the existence of an ether—not the kind of ether used as an anesthetic but the intangible, imponderable medium which was supposed to pervade all space. Purely an hypothesis, the idea of an ether proved so useful, so satisfied the requirements of innumerable physical phenomena, that today, when as a consequence of the Einstein theory and the quantum theory it is no longer essential, it is very difficult to conceive of a space devoid of it. As a vehicle for the transmission of light and as a medium in which to imagine an electric or magnetic field, the conception of an ether is invaluable and while it may be possible that no such medium as an ether exists, it is difficult to explain light and other radiation phenomena without it.

ELECTRIC FIELD THEORY OF THE ETHER

In explaining an electric field, it is obviously necessary to conceive of something in the space surrounding the charge producing the field. Whether we think of the field as a distortion or strain in the space medium itself or consider the space medium to be something emanating from the charge, the result is the same—something in the space is different in the presence of a charge than it is without it. According to one theory, which has much to recommend it, the ether is considered as being the combination of the individual fields of all the electric charges in the universe.[1] Thus, in Fig. 45, a negative and positive charge are shown close together; the electric field of each, individually, has a radial distribution as indicated by the dotted lines. At any point in space, the actual electric field so far as these two charges are concerned, is obtained by combining vectorially, the two separate radial fields. The actual field is thus constructed at several points as in Fig. 45. In a similar manner, all other charges in the universe could be cared for and so the actual field at any point in space determined. Most of the phenomena such as radio waves, propagation of light, etc., which require for their explanation an ether with impossible properties, can be reasonably well pictured if we consider the ether as the superimposed electric fields of all the electric charges in the universe.

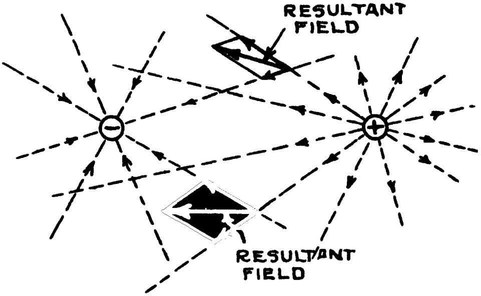

FIG. 45 THE ELECTRIC FIELD AT ANY POINT IS THE VECTOR RESULTANT OF THE SEPARATE FIELDS PRODUCED BY THE TWO CHARGES

While this concept is useful in explaining certain phenomena, it by no means explains the nature of the electric field nor of the ether. To the average reader, however, who needs something to visualize, it is well worth while and in the following discussion of the electromagnetic field we will keep it in mind. Regardless of how broad minded we may be, we must think of the lines of force as being made up of something.

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[1] Morecroft, Principles of Radio Communication, p. 6.

As was shown previously,[2] the electric field surrounding a stationary charge, say an electron, may be represented by straight lines of force drawn radially outward from the center of the charge. The direction of these lines of force, everywhere, represents the direction of the field and the number of lines per square centimeter or square inch represents the strength of the field. These lines of force must be considered as permanently attached to the charge like so many stretched rubber bands. In fact, whether the electron actually consists of a small charge located at O, Fig. 46, or whether the modification of the ether or space itself constitutes the electron is an unanswered question, but so far as theoretical considerations are concerned it

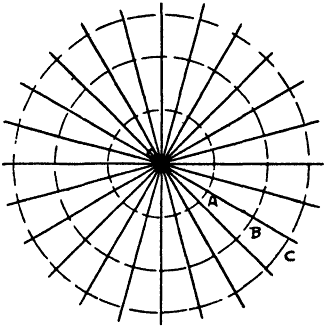

FIG. 46. REPRESENTATION OF THE ELECTROSTATIC FIELD SURROUNDING A STATIONARY ELECTRON

The dotted lines A, B, and C, represent the equipotential surfaces. This diagram must be regarded as a cross section through a sphere, for the lines of force around the charge extend outward, radially in all directions.

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[2] Page 45.

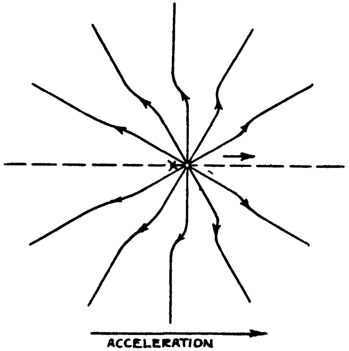

FIG. 47. THE DISTORTED FIELD ABOUT AN ELECTRON AN INSTANT AFTER IT HAS BEEN SET IN MOTION TOWARD THE RIGHT

Since the lines of force are thought of as non-rigid lines attached to the charge, it is evident that when the charge is suddenly set in motion, the movement of the lines of force will lag behind that of the charge. See Fig. 48.

makes no difference. It can be shown that a charge which is uniformly distributed over the surfaces of a sphere acts as if the whole charge were concentrated at the center of the sphere.

EFFECT OF MOTION OF ELECTRIC CHARGE UPON DISTRIBUTION OF FIELD

Suppose, now, that the stationary electron depicted in Fig. 46 is suddenly set in motion at a uniform speed

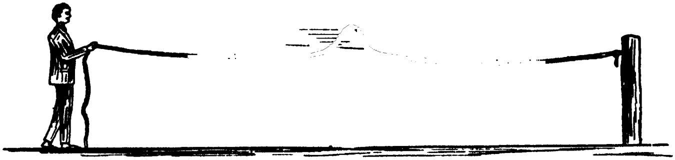

FIG. 48. WHEN ONE END OF A ROPE IS SUDDENLY JERKED IN THIS MANNER, A WAVE WILL TRAVEL TO THE OTHER END

along a straight line toward the right; let us examine the state of affairs at a subsequent instant. It is obvious that at some places sufficiently remote from the charge, the field will be unaware of the alteration that has just been made in the charge's motion and that the lines of force at those places will still be pointed toward the point where the charge was before it was set in motion. It is also evident that there are some points so near the electron that the field has completely adjusted itself to the new condition and here the lines will point directly to the actual position of the charge. From this, it follows that at some points intervening between the two regions, the lines will be bent, as shown in Fig. 47. In

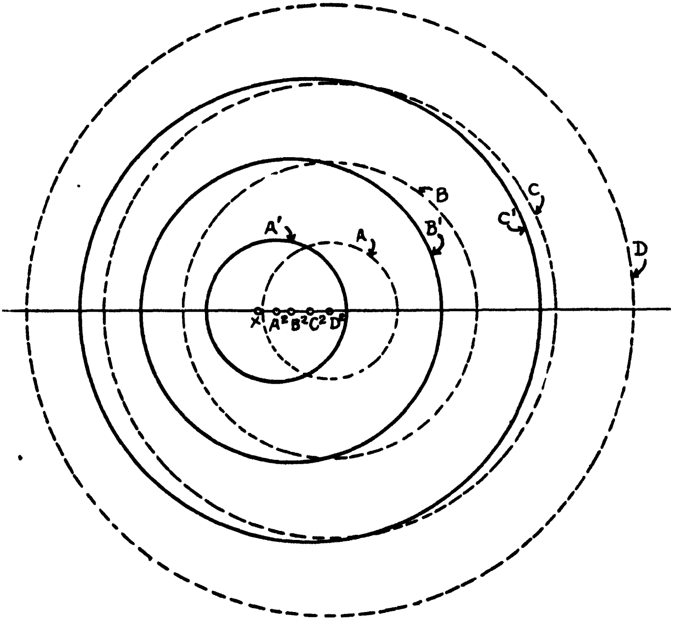

FIG. 49. DIAGRAM SHOWING THE DISPLACEMENT OF THE EQUIPOTENTIAL SURFACES DUE TO MOTION OF THE CHARGE

other words, the field surrounding an accelerating electron is no longer completely radial to the electron as is the case when it is stationary.

If the electron, which has been set in motion, is permitted to move at a uniform velocity, it will be evident that the point where the "bend" or shift in direction of the lines of force occurs will travel outward in a manner similar to that in which a wave will travel along a rope when one end is suddenly jerked to one side. In the case of the field, the speed at which this wave moves, is the same as the velocity of light, i.e., 186,000 mi. per sec.

This time lag in the effect of motion of the charge to be communicated to the electric field has many interesting consequences and we shall have occasion to refer to it again in connection with other matters concerning the electron but, for the present, it will only be necessary to remember that the field around a moving electron has a different shape from that around the same electron at rest.

DISTRIBUTION OF EQUIPOTENTIAL SURFACES AROUND CHARGE

Before we proceed with an explanation of a magnetic field, however, it will be well to show what is meant by the equipotential surfaces around a charge. Referring to Fig. 46, it will be noted that in addition to the radial lines of force, a number of concentric circles are drawn around the charge. These circles, in reality spheres, for the diagram must be regarded as a cross section through a sphere, are circles or surfaces of equal potential because all points along the circumference (or on the surface of a sphere) are the same distance from the center. For this reason, they are called equipotential circles or surfaces as the case may be.

Suppose again, as in the previous case, that the charge at the center is suddenly set in motion. The electric field immediately surrounding the electron will tend to move with the electron and as a consequence, the equipotential surfaces in that portion of the field will be shifted in the direction of motion of the charge. Thus the equipotential surfaces will no longer be concentric. The effect is illustrated in Fig. 49 in which the dotted circles A, B, C and D are the equipotential surfaces of a stationary charge at D_2. The solid circles A^1, B^1, C^1 and D are the same equipotential surfaces shown by the dotted circles but represent their position for the moving electron during the time it has moved along the line M-N from D_2 to X. The circle A^1 is the equipotential circle A and its position is still the same as though the electron were still at A_2. In other words, this circle is not yet aware of the fact that the electron has moved from A_2 to X. Similarly, the circle B^1 is not yet aware of the fact that the electron has moved from B_2.

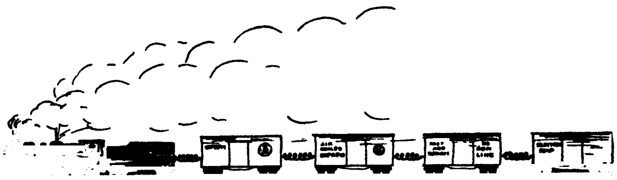

FIG. 50. THE EFFECT OF MOTION OF A CHARGE IS TRANSMITTED TO DISTANT PARTS OF THE FIELD SIMILAR TO THE MANNER IN WHICH THE MOTION OF THE ENGINE IS TRANSMITTED TO THE CARS IN THIS DIAGRAM

MECHANICAL ANALOGY ILLUSTRATING EFFECT OF MOTION ON ELECTRIC FIELD

The effect is very much the same as that which occurs in starting a train of cars which are coupled together by elastic bands or springs as shown in Fig. 50.

The instant the engine starts to move, the spring between it and the first car is stretched until the pull is sufficient to move the first car; this starts and stretches the spring between it and the second car until the third car starts. In this way the cars begin to move successively until finally the last car begins to move. The relative position between the cars will then be maintained a constant if the speed of the train remains uniform.

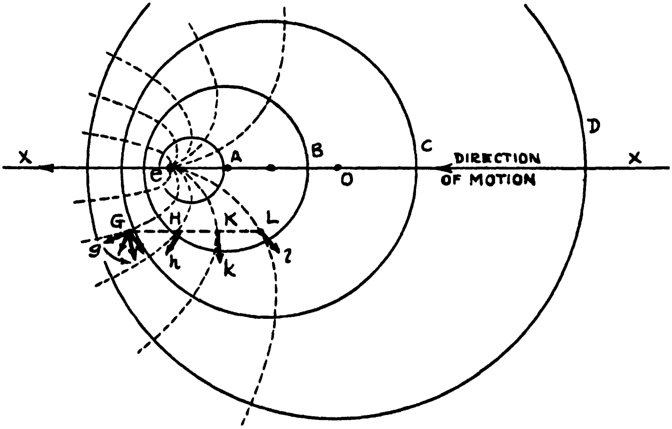

FIG. 51. REPRESENTATION OF THE FIELD AROUND A MOVING CHARGE

With this picture clearly in mind, it will be possible to show that the lines of force of the electrostatic field around a moving electron at any instant are curved as shown in Fig. 51. Here the direction of the field is obtained by drawing lines of force, through the center charge and normal to all equipotential surfaces at the points of intersection.

This change in shape of the electrostatic field, due to the motion of the charge, leads to some extremely important consequence. Referring again to Fig. 51, let us consider a point G, fixed in space and located outside of the line X-X. With the moving charge in the position shown, the field at point G will have a direction Gg, tangent to the line of force passing through the point G at that particular instant. As the electron moves along the line X-X toward the left, different lines of force will pass through G. Thus, where the charge e has moved along XX over total distances equal to GH, GK, GL, the field at G will successively assume directions parallel to Hh, Kk, Ll.

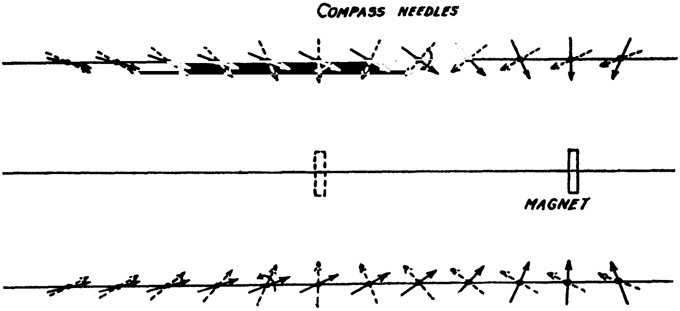

FIG. 52. SIMPLE MECHANICAL-MAGNETIC ARRANGEMENT TO ILLUSTRATE PRODUCTION OF ROTATIONAL STRAIN

In this arrangement a number of compass needles are pivoted along two parallel lines, as shown, while a small permanent magnet is arranged to move horizontally between them. The compass needles represent the lines of force; the magnet the electric charge. When the magnet is moved, the needles will slowly rotate about their axes.

It is evident, then, that as the electron moves along the line XX, the field at a fixed point in space G, will be along a straight line passing through G contained in the plane of the paper and gradually rotating around that point. In addition to the radial strain in the space medium due to the presence of the electron, a torsional or rotational strain is set up. This torsional strain in the space medium occurs along a line perpendicular to the direction of motion of the electric charge setting up the field and perpendicular also to the directions of the electrostatic field at the point considered. This force is called an *electromagnetic* force.

This conception may, perhaps, be made a little more clear if we compare it to the arrangement shown in Fig. 52. This diagram shows a small bar magnet arranged between two rows of magnetic needles, pivoted so as to rotate freely. The needles represent the lines of force of an electric field and the bar magnet an electric charge. With the magnet in the position shown, the needles will be attracted to it and will arrange themselves along lines connecting their centers and the bar magnet. If, now, the magnet is moved along the line AB in the direction of B, the needles will gradually be rotated about their axes. When the magnet is at the center as shown by the dotted rectangle, the needles will have assumed positions indicated by the dotted needles.

This is, of course, a crude comparison but it will at least indicate how a horizontal motion of a charge is capable of producing a rotational movement of the lines of force constituting the field.

The picture presented by the magnetic needles and also by the explanation of the rotating field itself is only half complete. In both cases, we indicated the rotation of only those elements in the plane of the paper. Since the lines of force shown for one plane, Fig. 51, exist identically for all planes containing the lines XX, the electrostatic and electromagnetic fields for the point G will have the same values respectively for all points of the circle described by point G, when Fig. 51 is rotated about the line XX. In other words, the picture presented by the needles in the above analogy would be more accurate if the needles were pivoted along the circumference of a number of rings, as shown in Fig. 53 and the magnet moved along a straight line through

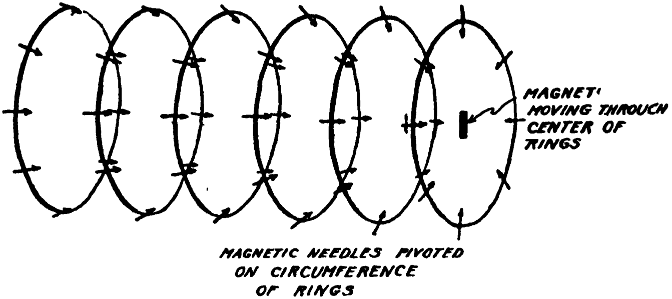

FIG. 53. A MORE CORRECT METHOD OF SHOWING PRODUCTION OF THE ROTATIONAL STRAIN

This arrangement is similar to that of Fig. 52 but in this case the needles are pivoted on a number of loops. This shows the action in three dimensions.

the center of the rings. This arrangement, while virtually the same as that shown in Fig. 52, gives a picture in three dimensions.

In Fig. 52 is shown a single magnetic loop, due to motion of the electric charge e. In this diagram f is the direction of the electrostatic field. The gradual rotation of this line f about the circular axes g produces a torsional strain along the circle g which is the electro-

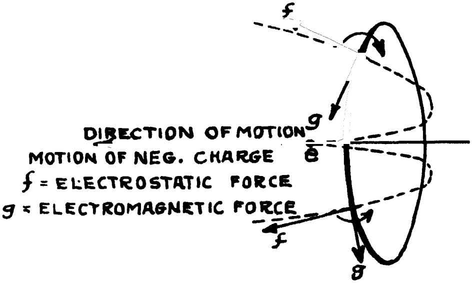

FIG. 54. A SINGLE LOOP OF MAGNETIC FIELD

The curved line f is the line of electrostatic force due to the moving charge e. As the charge moves the line f is rotated about the axes g, causing a torsional strain along g. The direction of g, which is the direction of the magnetic field, is tangent to the circle at any point.

magnetic force. It will be noted that the direction of the electromagnetic force at each point of the circle will be tangent to the circle.

From the foregoing explanation, it will be evident that the magnitude of this electromagnetic strain depends both on the value of the electrostatic field and on the rate at which its direction is turning around the point considered. It, therefore, depends, for a given point in the field, on the value of the moving charge, on its speed of motion and on the shape of its trajectory. If the direction of motion of the charge reverses, the direction of rotation and also the direction of torsional strain will be reversed.

In another article, we shall endeavor to show how this theory of electromagnetic force ties in with the known laws of the electric current and we shall also discuss the forces involved during the motion of an electric charge. This part of this book may seem rather tedious and unduly detailed but it is of tremendous importance and from this standpoint a detailed treatment is justified.

In the meantime, it is reassuring to know that our electron still serves us faithfully in our tortuous journey through electrical phenomena. So far, all physical, chemical and electrical phenomena that we have encountered has been explainable in terms of its properties and if this were a mathematical treatment instead of a purely descriptive work, it would be found that even more perfect conformity would obtain.

CHAPTER XIII

THEORY OF THE SOLENOID

IT WAS A kind streak in Nature that induced her so to arrange things that the movement of an electric charge gives rise to the production of a magnetic field, for it is probable that 99 per cent of all electrical apparatus depends for its operation upon the existence and action of this magnetic field. Every electric generator, every motor and transformer, every electric bell, all electrical communication systems in some way or other utilize magnetic fields produced by moving charges.

We have shown, in the preceding article, that the movement of an electric charge and its electrostatic field results in the production of an electromagnetic strain, the magnitude of which is proportional to the value of the moving charge, its speed and the shape of its path. We have shown also, in earlier articles, that what we recognize as an electric current is in reality a stream of moving electrons or ions. Knowing these two things, it would be natural to expect that an electric current would be surrounded by a magnetic field, the magnitude of which would depend upon the intensity of the current. This, as every reader, no doubt, knows, is true—every electric current has associated with it a magnetic field the strength of which is proportional to the strength of the current.

FORCES INVOLVED IN THE MOTION OF A CHARGE

Before we consider the magnetic effect of the electric current as a whole, it will be interesting to investigate more closely the forces involved during the time that an electric charge is in motion. What, for instance, is the effect of the electric or magnetic field upon the electron itself? Is there any reaction of the field upon the charge and if so what is its nature?

It has been demonstrated that when a charge is set in motion, the electrostatic field is distorted; the equipotential spheres assuming eccentric positions with re-

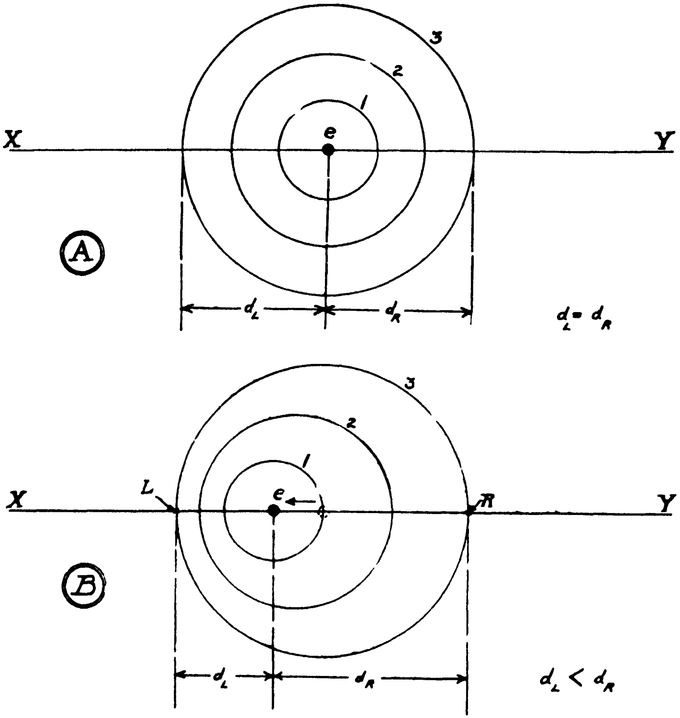

FIG. 55. ILLUSTRATING THE MANNER IN WHICH MOTION OF A CHARGE PRODUCES AN UNEQUAL DISTRIBUTION OF POTENTIAL GRADIENT

At A are shown three equipotential rings surrounding a charge e at rest. At B is pictured the same charge after it has been set in motion toward the left. The equipotential rings are eccentric, making the distance d_L from the charge to point L shorter than the distance d_R from the charge to point R. Since both of these points are at the same potential, it is obvious that the potential gradient must be steeper ahead of the moving charge than it is behind it.

spect to the charge. Thus, in Fig. 55, the equipotential rings surrounding the charge e, when at rest, are concentric as shown at A but are displaced as shown at B when the charge is set in motion towards the left. The amount of eccentricity is dependent upon the speed of the charge as can be seen from the equation,

$$\frac{d}{r} = \frac{s}{V}$$

where d is the distance between the charge and the center of the equipotential sphere considered, r, the radius of the sphere; s, the speed of the charge, and V, the velocity at which the effect of motion of the charge is transmitted to distant points of the field.[1] From this it is evident that the amount of distortion is directly proportional to the speed of the charge.

Because of this distortion of the field around a moving charge, the potential gradient ahead of the moving charge is greater than it is behind it. This is evident if we refer to Fig. 55B. A point L on the equipotential ring 3 where it crosses the line XY to the left of the charge e is closer to the charge e than another point R diametrically opposite and to the right of e. Yet these two points are at the same potential, for they are both on the same equipotential circle, hence, the potential gradient is steeper to the left of e than it is to the right. Due to this unequal distribution of potential gradient around the charge, a force is exerted by the field upon the charge in such a direction as to tend to move the charge toward the center of the equipotential spheres. This force, therefore, is opposite to the motion of the charge and its magnitude is proportional to the speed of the charge—the greater the speed, the greater the opposing force.

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[1] Ordinarily, this speed, where the field is in air, is the speed of light or 186,000 mi. per sec.

ELECTROMOTIVE FORCE AND COUNTER ELECTROMOTIVE FORCE

Thus, the motion of the electron and the consequent distortion of the electrostatic field require the continuous application of a force in the direction of motion, this force, producing the motion we call the electromotive force while the reactive force exerted by the field is called the counter electromotive force.

As long as the speed of the electron or other charge is constant, these two forces will remain in equilibrium. If any attempt is made, however, to speed up the charge by increasing the electromotive force, the eccentricity of the field will increase and the unbalance between the potential gradient in front and in back of the charge will also increase. An increase in electromotive force, therefore, results in an immediate increase of counter electromotive force and the effect is a tendency to prevent any increase in speed.

In a similar manner, when the electromotive force is reduced the counter electromotive force will be greater than the electromotive force and will tend to drive the charge backwards. A backward motion, however, would immediately bring about a force opposed to the force producing that motion and this new force would tend to keep the charge moving in its original direction.

EFFECT IS SIMILAR TO THAT OF INERTIA IN MECHANICS

Thus it is seen that the distortion of the field around a moving electron tends to prevent any change in motion of the charge. The effect is similar to the effect of inertia in mechanics except that in the case of the electric charge, the apparent mass varies with its velocity. When the charge is at rest, its apparent mass is zero. As the speed increases, the mass increases and at the speed of light, theoretically its mass would become infinite. Of course, as has been shown by Einstein, a charge could never move at the speed of light, so the possibility of infinite mass of an electron becomes merely an interesting speculation. That the mass increases as the speed increases has been demonstrated by the action of the electron in the vacuum tube. At the high velocities attained by the electron in certain vacuum tube experiments, the mass of the electron increases appreciably.

The reaction of the field upon the moving charge is due to the magnetic field, which we have seen was, in turn, the result of motion of the charge. When the charge is traveling at a uniform speed, the force applied to it (electromotive force) is exactly balanced by the reactive force (counter electromotive force) and the resultant force is zero. Since there is no force acting on the charge, there is no acceleration.

When the charge was first set in motion, however, there existed no reactive force. The driving force in setting the charge in motion and by creating the magnetic field, accomplished a certain amount of work, in doing which a certain amount of energy was expended. When the driving force is exactly counterbalanced by the reactive force, no further work is done.

ENERGY IS STORED IN MAGNETIC FIELD

The energy expended in thus setting the charge in motion and in the creation of a magnetic field is stored up in the magnetic field itself where it exists as potential energy. In setting the charge in motion, a certain amount of the electrostatic energy of the charge is transformed into an equivalent amount of electromagnetic energy, this transformation requiring a certain amount of work on the part of the driving force. This transformation, once established and having exhausted the energy of the source supplying the driving force, the

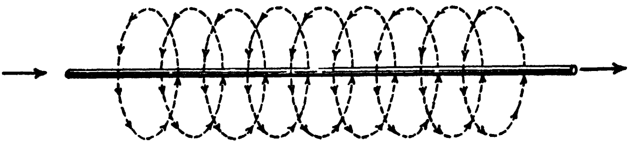
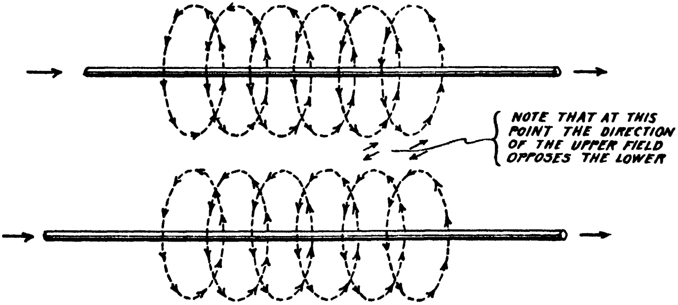


FIG. 56. MAGNETIC FIELD AROUND A STRAIGHT CONDUCTOR CARRYING CURRENT

conditions remain as they are; that is, the charge remains in motion at a constant speed.

When the motion of the charge is to be stopped, it is evident that a force must be applied in a direction opposite to the direction of the driving force. An amount of energy must be applied, exactly equal in amount but opposite in direction to that which was expended in establishing the motion of the charge. This force is available in the magnetic field and comes into play the instant the driving force is removed or reduced. In other words, the removal of the driving force (electromotive force) is accompanied by the disappearance of the electromagnetic energy and its restoration in the electrostatic field of the charge.

Thus it is apparent that although the creation of



NOTE THAT AT THIS POINT THE DIRECTION OF THE UPPER FIELD OPPOSES THE LOWER

FIG. 57. MAGNETIC FIELDS ABOUT TWO WIDELY SEPARATED STRAIGHT CONDUCTORS CARRYING CURRENTS IN THE SAME DIRECTION

the magnetic field when a charge is set in motion requires the expenditure of a certain amount of energy, this energy is returned to the charge or rather to the electrostatic field of the charge, when the motion is stopped. The total amount of energy stored in the two fields (the electrostatic and electromagnetic) at any instant is constant. A transformation from one of these fields to the other occurs when an electric charge is stopped or started, each transformation creating a force opposed to that causing the transformation and requiring the expenditure of a certain amount of energy on the part of the force causing the transformation.

This interchange of energy between the electrostatic and the electromagnetic fields is of great importance in electrical engineering, particularly in the case of resonance phenomena in power factor control and radio work.

MAGNETIC FIELD AROUND A CONDUCTOR CARRYING CURRENT

Since an electric current is in reality a number of electrons in motion, it must be evident to anyone that a current carrying conductor is surrounded by a magnetic field as pictured in Fig. 56. The wire serves very much as a pipe through which the electrons flow. Suppose now that we place two wires carrying streams of electrons in the same direction, parallel to each other as shown in Fig. 57. Since the currents are in the same direction, the direction of the magnetic fields will be in the same direction. At the point where the two sets of magnetic loops tend to touch, it will be noted that the directions of the magnetic fields oppose each other; hence, instead of each loop passing around its own wire, they find it more convenient to jump to the adjacent loop so that each loop of magnetic field makes a complete path around the two wires as shown in Fig.

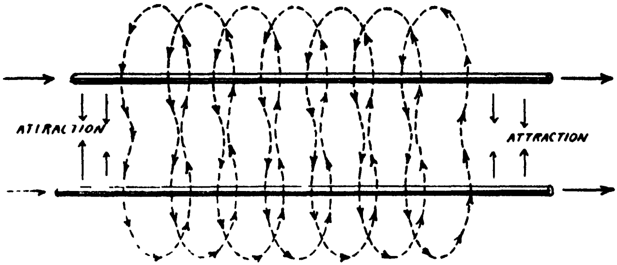


FIG. 58. WHEN TWO CONDUCTORS CARRY CURRENT IN THE SAME DIRECTION THE LINES OF MAGNETIC FLUX WILL ASSUME THE FORM SHOWN HERE

In this case the loops of force make one complete circuit around both of the wires instead of passing around them individually as in Fig. 57. This is due to the fact that at the point between the wires where the respective fields tend to touch, the direction of the loops oppose each other; hence they pass from one to the other as shown. Under these conditions the conductors are attracted to each other.

58. Under these conditions, because of the tendency of the magnetic loops to shrink like stretched rubber bands, the two conductors are drawn together. In other words, parallel streams of electrons flowing in the same direction, attract.

Let us now assume the two conductors to be carrying streams of electrons flowing in opposite directions.

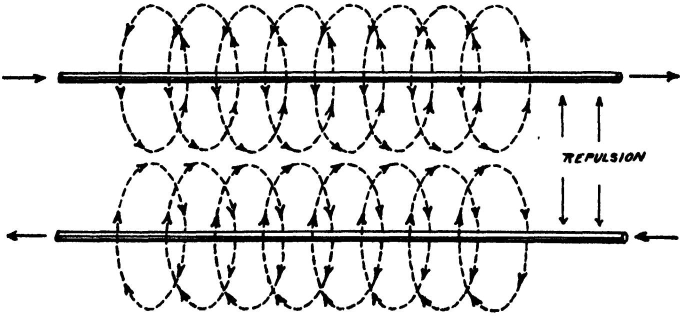


FIG. 59. FIELDS SURROUNDING TWO CONDUCTORS CARRYING CURRENTS IN OPPOSITE DIRECTIONS REPEL EACH OTHER

In this case, the lines or loops of force about them are swirling in the same direction and there will be no tendency for the two sets of loops to merge. Instead, they will repel each other as shown in Fig. 59. Thus, parallel streams of electrons flowing in opposite directions repel each other.

That these two assertions are correct can easily be proved by the arrangement shown in Fig. 60. Here two light aluminum rods are freely suspended so that their lower ends are just immersed in a shallow tray of mercury; they are therefore free to move under the slightest force which may be applied to them. Suppose now that an electric circuit is so arranged, first, so as to cause the rods to carry currents in the same direction as shown in Fig. 60A and second so as to cause them to carry currents in opposite directions as in 60B. In the first case, the lower ends of the rods will be drawn together, due to the attractive influence of the magnetic

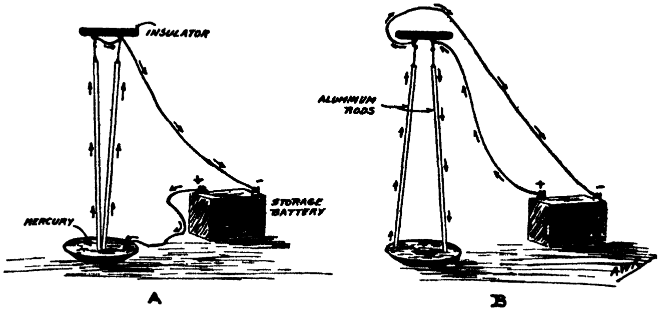


FIG 60. AN EXPERIMENT TO SHOW THE CORRECTNESS OF THE THEORY OF REPULSION AND ATTRACTION BETWEEN CURRENTS FLOWING IN THE SAME AND IN OPPOSITE DIRECTIONS

In the experiment two aluminum rods are suspended so that their ends are just immersed in a bath of mercury. When currents are passed through the rods in the same direction the rods are attracted as at A, while, when the currents flow in opposite directions as at B, they are repelled.

fields surrounding them, while in the second case they will be forced apart because of the repulsive force.

FIELD SURROUNDING A CONDUCTING LOOP

Anybody having had anything to do with electrical devices of any type is familiar with the fact that all electrical equipment is provided with coils of wire in various forms. Wherever a magnetic field is present, there will be found a coil or helix of some sort. Why is this? We have just learned that a current carrying conductor is surrounded by a magnetic field. In what manner then, is a coil associated with such a field? These questions we will now endeavor to answer.

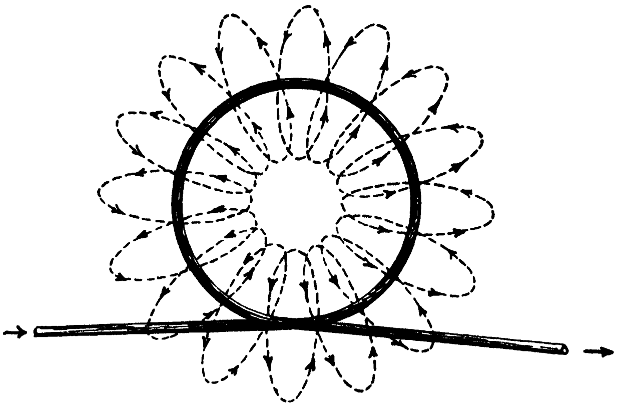


FIG. 61. MAGNETIC FIELD AROUND A LOOPED CONDUCTOR
All of the lines of force enter the loop at one face and leave at the other.

By means of Fig. 59, we demonstrated how the magnetic fields surrounding two parallel conductors carrying currents in opposite directions repelled each other. Suppose, however, instead of having two separate conductors, each supplied from a different source, we merely bend the upper wire back upon itself. Brief consideration will make evident that with this latter arrangement, in so far as the magnetic fields are concerned, the effect will be the same as that produced by Fig. 59. Suppose further that instead of merely bending the wire back on itself it is bent in a complete circle as shown in Fig. 61. Because the current on one side of the loop is flowing in the opposite direction from that on the opposite side all the magnetic lines will enter the loop at one face and leave at the other.

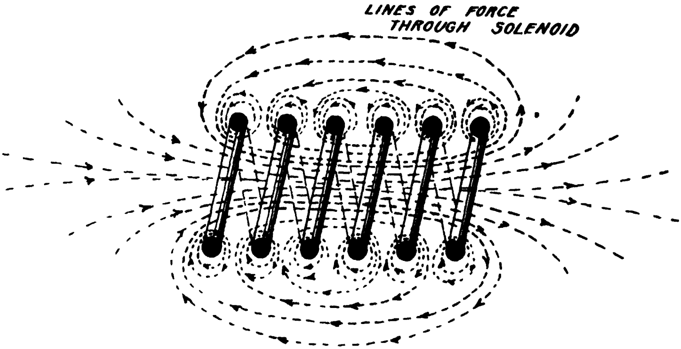


FIG. 62. SHOWING THE INCREASE IN FLUX RESULTING FROM WINDING THE CONDUCTOR IN THE FORM OF A HELIX OR SOLENOID

With such an arrangement, due to the combined action of all the magnetic lines of force concentrated at the center of the loop, a very much more powerful field is set up than is possible by a straight conductor. This is the great advantage of the coil over the straight wire and is the reason coils are used in all electromagnetic devices.

Instead of one turn or loop of wire, let us continue the process by making a helix as shown in Fig. 62. The effect is obvious, from a study of the diagram. A large number of the lines of force produced by each turn will encircle the entire helix, producing a very strong field at the center of the coil.

If the turns are brought still closer together as in Fig. 63, a still larger number of lines of force will be concentrated at the center, resulting in a still stronger field.

This, briefly, is the principle upon which the solenoid or electromagnet operates. The strength of the magnetic field at the center of the coil, is directly proportional to the number of turns in the coil, and to the strength of the current flowing through them. It is for this reason that in the design of all electromagnetic equipment the "ampere turn" is used. The ampere turn is a unit representing the ability to produce a certain magnetic intensity. In other words, the number of lines of force produced by a given helix is always proportional to two factors: first, the current in amperes flowing in the helix; second, the number of turns of the helix.

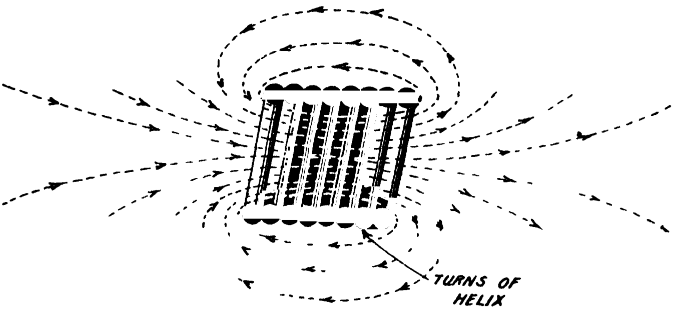


FIG. 63. BRINGING THE TURNS CLOSER TOGETHER, AS SHOWN IN THIS DIAGRAM, RESULTS IN A STILL FURTHER INCREASE IN FLUX

In making use of the term ampere, here, we do so merely because this term is so generally known to be the practical unit of current. It would be more consistent for us, in attacking the problems of electrical engineering by means of the electron, if we used the electron-turn. This, however, would be an exceedingly small unit to use in practice, since an ampere represents the passage through a conductor of 6,300,000,000,000,000,000, electrons per second. So the ampere turn represents the magnetic field which is produced by the above number of electrons traveling around one turn of wire in one second.

CHAPTER XIV

REACTION BETWEEN CURRENT CARRYING CONDUCTORS

WHEN TWO CONDUCTORS, carrying current in the same direction are placed parallel to each other they will be drawn together because of the interlinkage of their magnetic fields. This action was discussed in detail in the previous chapter.

With a knowledge of such attraction (or repulsion in case of currents flowing in opposite directions) the question arises as to what effect such deflections have upon the currents in the conductors. We know from simple mechanics that to every physical action there is an opposite and equal reaction. What, if any, is the reaction in this instance?

To explain this, it will be necessary to consider again the production of a magnetic field by a current. An electric current, it will be recalled, is simply the parallel motion of a large number of electrons. Since each electron as it moves produces a magnetic field, it is obvious that the intensity of the magnetic field due to a current is equal to the sum of the field intensities of the individual charges or electrons.

In Fig. 64 are shown two parallel wires, each carrying a certain current I. Each current creates a magnetic field of a certain intensity $\emptyset$. If the wires are placed close to each other, as in the diagram, the total field surrounding the two wires will be $2\,\emptyset$. Thus, the effect of placing the two wires close together is the same as though the current in one wire had been doubled, that is, increased to 2 I. Since this relation holds true for all values, it may be written in the form of an equation

$$\frac{\emptyset}{I} = L$$

in which $\emptyset$ is the intensity of magnetic field surrounding the circuit, I is the current in the circuit, and L is a constant of the circuit, commonly known as the *inductance* of the circuit.

NATURE OF INDUCTANCE

Inductance, unlike resistance, is not a function of the material of which the conductor is made but is a function of the shape of the circuit. This will be evident when it is recalled that the intensity of magnetic field due to a certain current in a conductor is dependent upon the shape of the conductor. Since inductance is a property dependent upon the magnetic field, it follows that inductance is a function of the shape of the circuit; the inductance of a certain length of conductor made into the form of a coil or solenoid being greater than that of the same length of conductor stretched out as a straight wire.

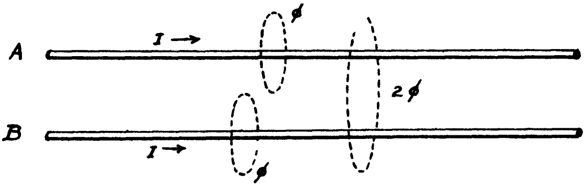


FIG 64. TOTAL FLUX SURROUNDING TWO WIRES, IS SUM OF FLUX SURROUNDING INDIVIDUAL WIRES

When a current is sent through a conductor, we have seen that when the current is first started a certain amount of force must be applied in order to build up a magnetic field. Once the current reaches a steady value, however, and the magnetic field is fully created, no more force need be applied. In actual practice, however, where the current passes through ordinary metallic conductors, a certain force must be applied to overcome the resistance of the circuit. This resistance is due to the fact that the moving electrons continually collide with the atoms of the material making up the conductor. This energy spent in overcoming the resistance is transformed into heat and will not be restored when the current is stopped. In this respect, it is unlike the energy spent in building up the field.

Suppose now we consider the circuit shown in Fig. 65, consisting of a coil in series with a battery and including a switch through which the circuit is completed. When the switch is closed, an electromotive force is suddenly applied to the electrons in the wire. This electromotive force will be spent in two ways as already explained, first in causing the electrons to move against the resistance offered by the molecules and atoms of the conductors, and second in effecting the distortion of the electrostatic field and setting up the magnetic field. The force required in the latter action is the same that

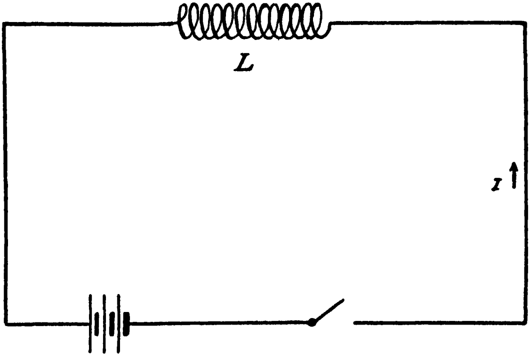


FIG. 65. SIMPLE CIRCUIT CONTAINING A SOURCE OF E.M.F. A SOLENOID AND A SWITCH

When the switch is closed the e.m.f. impressed across the circuit is spent in two ways, first, in overcoming the ohmic resistance of the conductor, and second in establishing a magnetic field through the coil L. The component used in overcoming the resistance is continually radiated as heat but that which establishes the field is needed only during the time the field is actually building up.

would be required to set the electrons in motion in vacuum.

ENERGY STORED UP IN THE FIELD

When the force (electromotive force) is first applied, all of it (ignoring here, that used in overcoming resistance) is available for accelerating the electrons. As the electrons start to move, however, the electric field is distorted and a reactive force (counter-electromotive force) appears as already explained. When the speed of the electron is such that the counter-electromotive force exactly balances the electromotive force, the speed remains constant and no more energy need be applied. The amount of energy that must thus be expended in establishing the steady value of current and in the creation of the corresponding amount of magnetic flux, will depend directly upon the inductance of the circuit. The greater the inductance the greater is the work required to start the current and the greater will be the energy restored to the circuit by the collapsing magnetic field when the electromotive force is removed. A large electric generator may have a great deal of energy stored up in the magnetic field of its field coils. For this reason, it is never wise suddenly to open the field switch of a generator, since the sudden collapse of the magnetic field may build up a high voltage which will flash across the contacts of the switch in the form of a powerful arc. Field switches are usually provided with resistances which absorb this energy when the circuit is opened.

Referring again to Fig. 64 it must be evident that during the time that the current was building up, there was an unbalance between the electromotive force and the counterelectromotive force and therefore also a difference between the driving and reacting electrostatic fields. This produces a resultant electrostatic field, which is capable of acting not only upon the electrons in the conductor under consideration but also upon any other electrons that may happen to be in the field.

ELECTROMAGNETIC INDUCTION

Thus, if we place another conductor or coil in close relationship to the one shown in Fig. 65 as in Fig. 66, this resultant field will tend to accelerate any free electrons in this circuit. If this coil is closed upon itself as indicated, the electrons so set in motion will constitute an electric current. Thus it is possible, by means of a current flowing in one circuit, to induce another current in an entirely separate circuit having no electrical connection whatever with the first. This is known as electromagnetic induction and was discovered by Michael Faraday in 1831. It is the basic principle of all electric generators and motor equipment.

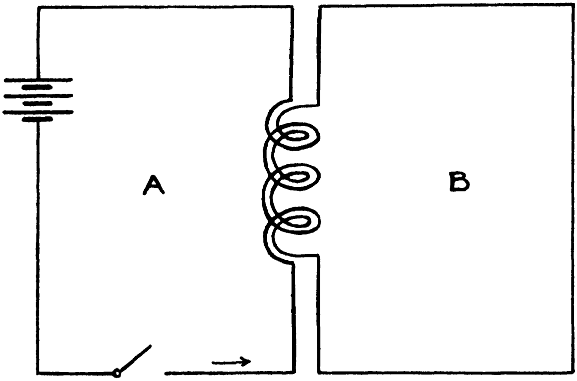


FIG. 66. CIRCUITS SHOWING THE PRINCIPLE OF ELECTROMAGNETIC INDUCTION

In this explanation, the curious reader may wonder just why the magnetic field should set the electrons in an outside conductor in motion. What is the mechanism involved?

To explain this, we must keep in mind the method of producing the magnetic field. In Fig. 67, at the left, is shown a circuit containing a source of electromotive force which in producing a current I establishes a magnetic field around the conductor A as shown. Suppose, now that the current is suddenly increased by increasing the electromotive force. It is evident that after the increase in current has occurred, the lines of force constituting the magnetic field will have increased in radii.

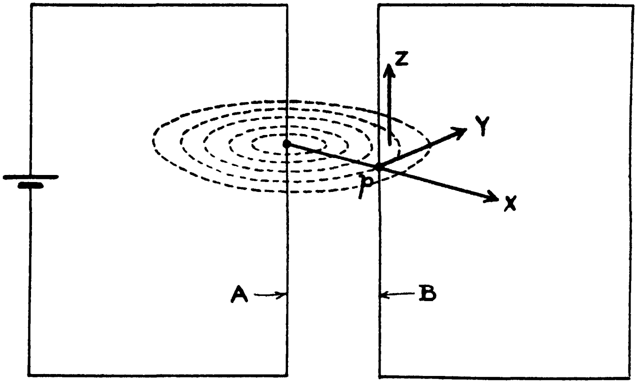


FIG. 67. TWO CIRCUITS, SHOWING HOW AN EXPANDING OR CONTRACTING FIELD IS CAPABLE OF INDUCING A CURRENT

In an adjacent circuit which does not contain a source of electromotive force, consider a point p on the conductor B. When the current in A is steady, the direction of the magnetic field due to this current at the point p will be in a direction X, that is, tangent to the circle of flux passing through that point. During the time that current in A was being increased from a value I, to a value I_2, the circle of magnetic flux was increased in radius and the magnetic force X was displaced without changing its direction. This displacement was along the line X.

Now, it is an interesting fact that many processes in nature are reversible and this is particularly true in electricity. We have shown how a moving electric charge will produce a magnetic field the direction of which is at right angles to the motion of the charge. In the same manner a moving magnetic field will produce an electrostatic field at right angles to the direction of motion of the field.

Thus in Fig. 67, the direction of motion of the magnetic field is in the direction X and with the direction of flux toward Y, an electric field, Z, will be produced. This electrostatic field, being parallel to the direction of the electrostatic field causing the increase in current I, is perpendicular to X and Y. If, under these conditions, an electric charge is placed at p, it will be set in motion along the line, Z, and in a direction depending upon the polarity of the charge. It will be recalled that a positive charge moves in a direction opposite to that of a negative charge when placed in an electric field.

It must also be remembered that these effects take place only when the magnetic field is actually expanding or contracting, that is, when the current in A is actually being increased or decreased. If the current is being decreased instead of increased as supposed, the reverse effect will take place. The tendency of the induced electromotive force, as this force Z is called, is always in a direction such as to oppose the force producing it.

REACTION OF MOTION OF CONDUCTOR UPON CURRENTS

This then provides us with a clue as to what happens in the conductors when two current carrying conductors are attracted or repelled, due to their magnetic fields.

It must be evident that the phenomenon described above will take place regardless of whether the secondary circuit (the right hand one in Fig. 67) carries a current or not. If it is already carrying current, the induced current will tend to diminish its flow.

In Fig. 68 are shown the same two conductors shown in Fig. 58 in the previous chapter. Because their currents flow in the same direction, their magnetic fields tend to pull them together. As the conductors approach each other, the magnetic field of one will cut adjacent conductor, thus inducing therein a current which opposes the current already flowing. Each conductor acts upon the other in the same manner, so the result of the attraction is a momentary diminution in the currents in both.

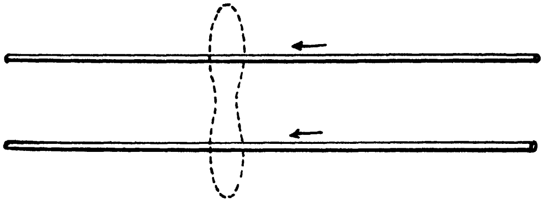


FIG. 68. WHEN TWO CONDUCTORS ARE MUTUALLY ATTRACTED DUE TO THEIR MAGNETIC FIELDS, THE CURRENTS IN THEM ARE MOMENTARILY DECREASED

It must be understood here that, in so far as the induced current is concerned, it makes no difference whether the motion of the field across the conductor is obtained by increasing the current, thereby causing the circles of force to expand, or whether one or the other conductor is moved bodily relative to the other. In each case, the field cuts the conductor, so to speak, and a current is induced.

If the conductors of Fig. 68 carry currents in opposite directions as in Fig. 69, the result is the same. In this instance, the conductors are repelled and the fields cut the conductor in a direction opposite to that which occurred when the conductors were attracted. This results in the induced current having an opposite direction relative to that in Fig. 68 but since the normal current is also in the opposite direction, the result is the same, i. e., the normal current is momentarily diminished. Since the impressed electromotive force remains constant, it is evident that more work is done during the momentary diminution in current. The work is that required to cause the deflection of the conductors.

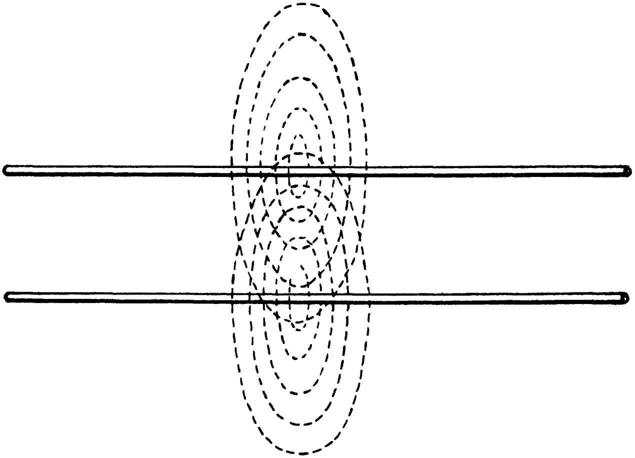


FIG. 69. REPULSION OF CONDUCTORS DUE TO MAGNETIC FIELDS ALSO CAUSES DIMINUTION OF CURRENT IN THE CONDUCTORS

We have now explained the three fundamental properties of the electric circuit, resistance, capacitance and inductance. No attempt has been made to discuss the various applications of these properties in electric circuits, nor have we attempted to enumerate the laws which govern their effect upon the electric current. In this series of articles, we are concerned primarily with the reason for the existence of these properties. We are less concerned, here, with a knowledge of the right-hand rule, which serves to express the directional relationship of magnetic flux, direction of motion and resultant force, than we are in knowing why an expanding or contracting electromagnetic field will set an electric charge in motion.

The hero of this story is the electron. His (or her, if you prefer) virtues are so numerous, that we shall require all the space at our disposal to recount them. The electron is at the root of everything in electrical science and it is the purpose of this series of articles to show how the electron is related to all the complex phenomena with which we are familiar today.

From a mere abstraction, the electron has grown to be the most important physical entity in the universe. Thus far, in these articles, we have been able satisfactorily to account for all electrical and physical phenomena in terms of its action. As we proceed, the idea of the electron as being the ultimate building block of the universe will become increasingly clear.

Before we proceed, however, it may be of interest to know something more about the manner in which the electron was discovered. This was promised in the first article of this series but was delayed purposely for the sake of providing the reader with a better knowledge of the apparatus used in its discovery. One of the elements involved in the discovery of the electron, for instance, is the displacement of an electric charge in an electric field and it would have been difficult to explain this to readers who had no previous knowledge of the principles involved in such displacement.

This has now been explained as have other phenomena, so that, in the next chapter dealing with the discovery of the electron, the reader need take little for granted.

CHAPTER XV

DETERMINATION OF THE MASS OF THE ELECTRON

THERE HAS BEEN much argument and many tomes have been written upon the ability of the human mind, aided by the five senses, to understand the true nature of things. When we look at a chair, for instance, is the chair really there or does the chair merely exist in our mind? Certainly, the chair we see in a dream is just as real as the one we see when we are awake. Of course, we can go over and touch the chair—feel it and thus we say we prove that the chair is there, but do we? How do we know that our sense of touch is not in league with our sense of sight to deceive us? When we see a chair, our eyes do not come in contact with the chair itself—all that really happens is that light waves (or particles, if you are a modernist in physics) of certain frequencies enter our eyes in a certain pattern which our brain, from experience, interprets as a chair. Cut off the source of illumination and the chair vanishes, until we walk in its direction and stumble over it. When this happens all the metaphysicians and philosophers in the universe, can not convince us that the chair was not there.

EXISTENCE AND PERCEPTION

Most of us, particularly when not engaged in philosophical thought, are pretty firm believers in our senses. When we can see a thing, we are fairly certain that something actually exists although we may have an entirely wrong idea as to what it is that we are looking at. Even when things are far away, we are likely to believe in their existence. And this is where the physicist who is dealing with atoms and electrons is at a great disadvantage, for he cannot show you the things he is working with and talking about. When the astronomer tells you he has just succeeded in measuring the diameter of a giant star in the constellation of Orion, you may doubt the validity of his measurement but when he takes you up on the roof and points out the star, you will have no doubts as to whether the star exists or not.

With the atomic physicist, things are different. When he tells you that he has just measured the diameter of the hydrogen atom, he cannot, like the astronomer, take you over to his microscope and show you the hydrogen atom. Here you may doubt not only his assertion that he has measured the atom but you doubt the very existence of the atom itself.

So when we talk glibly of atoms and electrons, what, after all, have we to prove that they really exist? In the articles that have preceded this, we have described them, their behavior, and have applied the principles of their behavior to an explanation of certain well-known properties of electric circuits. We have built up a theory of the structure of matter, showing how the electrons combined form atoms and how atoms combined form molecules. This theory is perfectly logical and agrees with known laws of physics, chemistry and electricity yet we admit that no one has ever seen a molecule, much less an atom or an electron. Then how do we know they exist?

PHYSICAL FACTORS IN PERCEPTION

Difficult as it is to answer this question, it is probable that we know as definitely that the electron exists as we do the chair referred to above. In either case, we are dependent upon the effect produced by the object upon certain other things which affect our senses. As explained above, when we see a chair we are merely conscious of a definite pattern produced on the retina of our eyes by electromagnetic radiation reflected from an object which we call a chair. The same is true when we look at a star in the heavens. The star we look at tonight may have been destroyed as the result of some cosmic collision, ten thousand years ago, yet we ordinarily would not argue with the astronomer as to whether it exists or not. We see it, therefore we think it exists. As a matter of fact, all that actually happens is that the light which left the star say one hundred thousand years ago is entering our eyes giving us the impression of a star.

Now an electron or an atom is entirely too small to reflect light, so there can be no hope that we can be made aware of its existence in the manner that a chair does. An electron or an atom, however, is endowed with energy which usually manifests itself as motion—extremely rapid motion. Suppose then that an atom or electron, moving at high speed, could collide with a much larger particle, say in the manner of a swiftly moving golf ball striking a football. It is evident that, in the latter instance, the energy of the golf ball would be imparted to the football causing it to move. Similarly, in the case of the atom and a large particle colliding, the large particle would be set in motion, indicating to us the presence of the atom. This, in fact, is just what actually occurs under certain conditions.

THE BROWNIAN MOTION

Just about one hundred years ago, in 1827, to be exact, an English botanist by the name of Robert Brown[1] noticed a peculiar wiggling motion in a drop of liquid which he was observing under his microscope. This wiggling, he first thought, was due to life, that is, the wiggling of microbes, but when he repeated the experiment with "dead" matter, the same motion was ob-

[1] Philosophical Magazine, IV (1826), p. 161.

served. Although this phenomenon was studied by numerous observers and became known as the Brownian movement, it remained unexplained for 50 yr.

In 1880, however, Carbonelle, a Belgian investigator, in a paper published by his collaborator, Thirion, made the suggestion that the Brownian movements might be due to the continual bombardment to which the particles in the liquid are subjected because of the thermal agitation of the molecules of the liquid. This question of thermal agitation, it will be recalled, was discussed in a previous chapter. Carbonelle's suggestion immediately set other investigators at work and in 1881 Bodoszewski, in studying the Brownian movements of smoke particles in air, saw in them an approximate image of the movements of the gas molecules as demanded by the

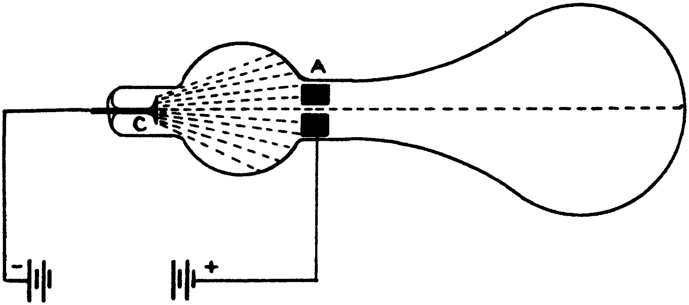


FIG. 70. DIAGRAM SHOWING THE PRINCIPLE OF THE CATHODE RAY TUBE

When a high potential is applied by means of a battery to the cathode C and a circular anode A placed in a tube from which most of the atmosphere has been exhausted, the few remaining molecules of gas in the tube will be ionized. The positive ions being attracted to the cathode strike it with such force as to liberate electrons which are immediately repelled from the cathode. Some of these electrons which are directed in the direction of the anode, pass through it, producing a cathode ray or electron stream in the space beyond the anode.

kinetic theory of gas. Subsequently, due to the brilliant work of Einstein in 1905, this idea was subjected to quantitative test and proved correct.

This Brownian movement is a marvelous phenomenon to observe under a microscope, for in those myriads of dancing particles we are seeing the consequence of actual collisions between molecules and larger particles. In the Brownian movement, then, while we are not actually observing the atoms or molecules, we are observing their direct individual effect upon particles we can see.

Now it is this type of investigation that must be pursued in any investigation of the atom and the electron; we must permit the electron to do something which will act upon our senses. In the Brownian movement, the atoms and molecules act upon the particles in suspension but in trying to observe the effects of the electron in this manner, the method fails because of the extremely small size of the electron.

Fortunately, if the electron lacks the mass possessed by the molecule, it has something or can be given something that will reveal its presence and that is velocity. As long as the electron remained comparatively stationary as it is in ordinary matter (ignoring here its rotational velocity) we knew little about it but once it was endowed with high velocities in the vacuum tube it began to tell its story.

THE CATHODE RAY

In Fig. 70 is shown a diagram of what is known as a cathode ray tube. This consists of a cathode or negative plate C and a tubular anode or positive ring A enclosed in a tube from which most of the air has been exhausted. If a comparatively high voltage is applied to these two terminals as shown, a number of the gas molecules still remaining in the tube may be ionized as explained previously[2] and the positive ions will be drawn to the negative plate with a velocity dependent upon the potential gradient of the field. If this is sufficiently high, the positive ions will strike the plate with such force that an electron will be jarred loose so to speak from the plate. Repelled by the negative plate from which they are derived, these electrons shoot off into space. Their energy is given to them by the battery which keeps the cathode negative by forcing on it electrons far in excess of its capacity for getting rid of them.

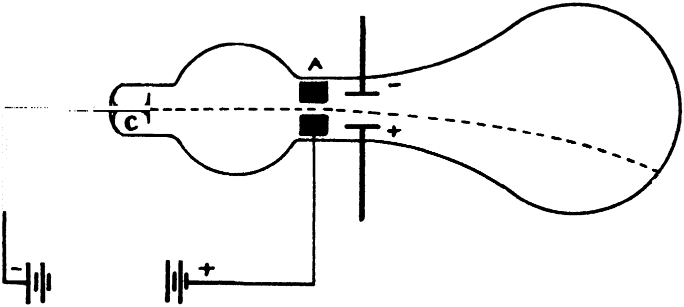


FIG. 71. SHOWING HOW THE CATHODE RAY IS DEFLECTED BY MEANS OF ELECTRICALLY CHARGED PLATES

As these electrons are shot off into space, they travel towards the walls of the glass tube. Many of them travel straight towards the anode. If the latter is made hollow as in the diagram, the tremendous velocities of the electrons will carry them straight through it, the attracting properties of the positive terminal having little or no effect on them. As a consequence there will be a stream of electrons in the space beyond the anode which can be used for experimental purposes.

This stream of electrons is, of course, invisible, but at the point where it strikes the glass walls of the tube it will cause the glass to phosphoresce, or if a chemically coated screen is placed at the end of the tube, it will phosphoresce brilliantly. By this arrangement the presence of the electron is revealed to the eye.

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[2] Page 60.

Suppose that, in addition to the cathode and anode in the tube, we arrange just beyond the hollow anode a set of plates as shown in Fig. 71 which can be charged positively or negatively by another battery. It will be recalled from our discussion of the conduction of electricity through gases, that when an electron is placed in an electric field, it will be acted upon by the field and will be drawn toward the positive terminal. It will be evident, therefore, that if a charge is applied to this new set of terminals in the cathode ray tube while the stream of electrons is passing between them, the electrons will be attracted to the positive plate and the stream as a whole will be deflected as shown. If the charges are reversed the deflection will be upward; if the charge is reduced or increased, the deflection will be reduced or increased.

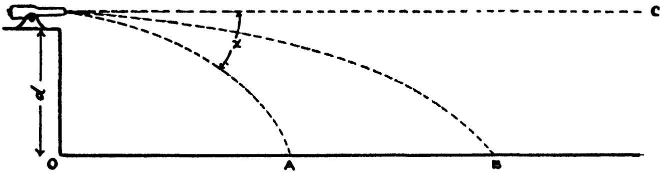

FIG. 72. DIAGRAM ILLUSTRATING THE ACTION OF GRAVITY AND SPEED UPON THE TRAJECTORY OF A PROJECTILE

In other words, by varying the electrical charge on the plates the direction of the stream of electrons can be changed at will. It is much the same action as occurs when the nozzle of a hose carrying a stream of water is moved back and forth—a slight movement of the nozzle causes a wide movement of the stream.

Also the cathode ray can be deflected by placing the tube between the poles of a magnet.

DETERMINING THE VELOCITY OF THE ELECTRON IN THE CATHODE RAY TUBE

J. J. Thomson made use of both of these methods in determining the velocity of the particles. The method he used consisted in permitting both an electric field and a magnetic field to act upon the ray at the same time and arranging the respective fields in such a manner that one would counteract the other. In other words, the effect of the electrostatic field which, say, deflected the ray upward was counteracted by a magnetic field which tended to deflect the ray downward. By properly proportioning the field strengths an exact balance between the forces was obtained and the ray would suffer no deflection.

Now it so happens that the ratio of these intensities depends only upon the velocity with which the particles are moving. The principle involved is the same as that which governs the trajectory of a projectile fired horizontally at some distance above the surface of the earth. If there were no gravitational attraction, a projectile would travel out horizontally when fired from the gun in Fig. 72. With the force of gravity acting upon the projectile from the instant it leaves the gun, it will be gradually pulled to earth and the trajectory instead of being a horizontal will take the form of a parabolic curve as shown at A for instance. Now the point at which the projectile strikes the earth, assuming a constant gravitational acceleration, is purely dependent upon the speed. If it leaves the gun with a certain speed, it will strike the ground at A. If the speed is increased, it will come down at, say, B. The time elapsed between the time the bullet leaves the gun and the instant it hits the ground is a constant regardless of the horizontal distance of travel.

Knowing the force required to deflect the trajectory of the projectile through a certain angle, the speed can be calculated.

These same principles hold in the case of the cathode ray and it was by a series of experiments based on this principle that J. J. Thomson determined the speed of the particles in the cathode ray. Thomson's equipment is shown in Fig. 73.

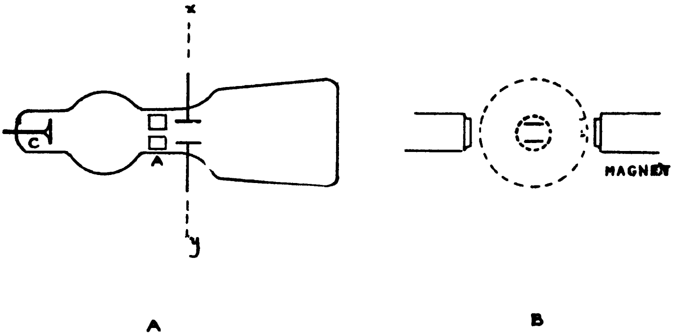

FIG. 73. THOMSON'S APPARATUS FOR DETERMINING THE RATIO OF THE CHARGE OF THE ELECTRON TO ITS MASS

A is a side view of the cathode ray tube showing the plate electrodes for deflecting the cathode ray by the electrostatic field. At B is shown a section through x-y showing the magnets for causing the deflection by the magnetic field.

THOMSON'S EXPERIMENTS IN DETERMINING THE MASS OF THE ELECTRON

Thomson next sought to measure the electric charge of the cathode ray particles but at that time it was not known how to measure this quantity directly, so he devised a method which gave the ratio of the charge on the particle to its mass. This was simple and was accomplished by merely using the electric charge to deflect the cathode particles. It is evident from a study of Fig. 72 that the acceleration to earth of the projectile is dependent upon the force of gravity, but that the horizontal distance it travels is dependent upon the mass of the particle.

Similarly with the cathode particles, the downward deflection depends upon the applied charge to the plates but the resistance to deflection depends upon the mass.

Thomson found that this ratio of the charge of a cathode particle or electron to its mass was just about 1700 times the similar ratio for the hydrogen ion in electrolytic conduction.

Assuming that the mass of the hydrogen ion[3] is essentially the same as that of the hydrogen atom, and that the charge on the cathode particle or electron is the same as that usually associated with the hydrogen ion, Thomson was forced to the astonishing conclusion that the mass of the electron was about one seventeen hundredth of the mass of the hydrogen atom. A similar research with similar results was conducted independently by Wiechert.

Here, then, was the first experimental evidence and intimation of a particle very much smaller than the hydrogen atom. Once this much was known, there came the question: What is the value of the charge itself? The definite answer to this finally came from Professor Millikan of the University of Chicago. Millikan's work in evaluating the charge on the electron will stand for all time as among the most brilliant and far reaching in the history of mankind.

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[3] The hydrogen ion, is the nucleus of the hydrogen atom. See discussion of ions, p. 65.

CHAPTER XVI

DETERMINING THE CHARGE ON THE ELECTRON

BEFORE MILLIKAN finally conducted his extremely ingenious experimental determination of the exact value of the charge of the electron, a considerable amount of preliminary work on the problem was done by other investigators. Once Thomson had shown that the mass of the electron was only one-seventeen hundredth that of the hydrogen atom, the question of the value of the charge itself took on a new significance and methods were soon devised to answer it. Before we discuss these methods, let us briefly restate the condition of affairs and the problem involved.

WHAT WAS TO BE DONE

Matter which heretofore had always been thought of as consisting of molecules and atoms, the latter being the smallest possible division of matter, was now, due to Crooke's experiments, shown to be made up of still smaller particles called electrons; the atom apparently was made up of these electrons. These electrons, Thomson had shown, were only 1/1700 the size of the smallest atom known, i. e., the hydrogen atom, and carried negative charges of electricity. The question now was, what is the value of this electric charge in terms of ordinary electrical units? The electron, it seemed, was not only the smallest particle of matter possible but its charge was also the smallest electrical charge that could exist in nature. The determination of this charge in terms of ordinary electrical units then was the problem that confronted the physicists in the late 1890's.

One of the first investigations of this problem was

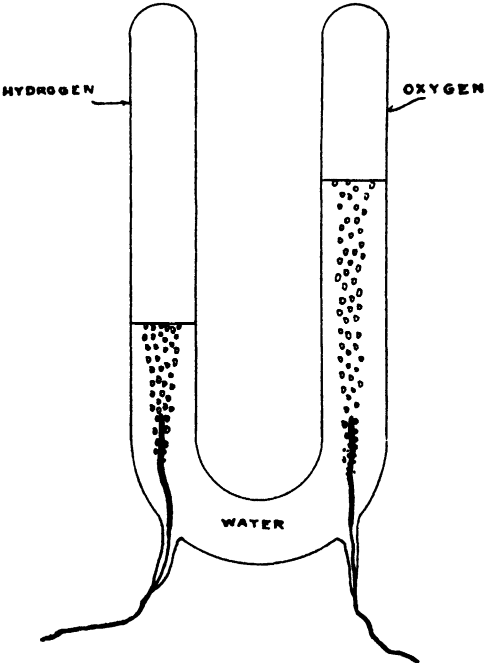

FIG. 74. AN ELECTROLYTIC CELL FOR THE PRODUCTION OF CHARGED OXYGEN GAS

When two electrodes are immersed in a conducting solution of water and connected to a source of direct e.m.f. hydrogen gas will be given off at one terminal while oxygen will be produced at the other. Most of the molecules thus produced are neutral, but once in a million times one escapes with an electrical charge. The gas produced, therefore, carries an electrical charge which can be measured by an electrometer.

made by Townsend in England. Townsend apparently was a man with no small imagination and with no little presumption. For who but a man with infinite confidence in his ability and with an ingenious turn of mind would presume to weigh a *cloud,* much less count the drops of water in a cloud? Yet that is just what Townsend did, and he did it well, although because of certain incorrect assumptions, his determination of the charge was incorrect.

Now, what on earth have clouds to do with the charge on an electron? This is a logical question and one that would be asked by any man but Townsend; however, we shall see.

ELECTRIC CHARGES ON GASES

It had long been known that gases could carry an electric charge; in fact, certain gases given off at the electrodes in an electrolytic bath were found to be naturally charged. Apparently the gas molecules[1] formed at these electrodes were not all neutral molecules—some of them, at least, seemed to have captured a charge and retained it.

Townsend, in attempting to measure the charge on certain gases found that when such charged gases were bubbled through water, they formed a cloud. This cloud could be completely removed by bubbling it through concentrated sulphuric acid which acted as a drying agent, but it was found that the instant this dried gas was admitted into the atmosphere of a room it again condensed moisture and formed a stable cloud.[2]

From this action, Townsend reasoned that the ions, that is, the charged atoms or molecules of gas, act as centers for the condensation of moisture from the air. Each ion, it seems, attracts a number of atoms or molecules of water to form a tiny drop. These droplets taken together form the clouds with which Townsend experimented.

It was evident, from experiments which had for their purpose the measurement of the electric charge of certain quantities of gas, that only a few of the gas molecules became charged. In other words, in the case of hydrogen gas escaping at the electrodes of an electrolytic bath, most of the molecules formed were neutral. Once in a million times, however, one of the molecules released escaped with a charge—that is, it captured an extra electron or escaped with less than its required number of electrons. These charged molecules, when projected into an atmosphere in which moisture was present or when passed through water, act as centers about which the molecules of water collect to form droplets.

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[1] Conduction in liquids, Chapter VII, page 66.
[2] R. A. Millikan, The Electron, p. 45.

Now, it occurred to Townsend that if each ion condensed moisture around it to form a single droplet, then the total number of droplets in a given cloud would represent the actual number of ions present. If this were true and if he had a means of counting the number of droplets, it would only be necessary to divide the total electric charge of a certain quantity of gas by the number of droplets of water formed, to obtain the value of the electric charge on each ion.

MEASURING ELECTRIC CHARGES BY ELECTROSCOPES AND ELECTROMETERS

It was a simple matter to measure the charge on the gas by means of a calibrated electroscope or electrometer. A gold leaf electroscope is shown in Fig. 75. It consists simply of a pair of gold leaf strips suspended in a glass jar so that an electric charge may be imparted to them by means of the metal rod passing through the top. If a positive or negatively charged body, say a stick of sealing wax, is placed in contact with the ball at the top of the jar, the charge on the sealing wax will pass down the rod to the gold leaves. Being similarly charged, the leaves will repel each other and will diverge as shown. The amount of divergence is a crude measure of the strength of the charge. An electrometer is built on similar principles but is fitted with a scale whereby the charge may be actually measured.

With an apparatus of this kind, then, it was a simple matter for Townsend to determine the total electrical charge per cubic centimeter carried by the gas.

His next step was to weigh the cloud formed around the ions. This he did by passing the cloud through a series of tubes containing chemicals which absorbed all the moisture without in any way affecting the gas itself. It was evident, therefore, that if he weighed the drying tubes both before and after the cloud had been absorbed, the increase in weight of the tubes would be a measure of the weight of the cloud.

Next he determined the average weight of the water droplets constituting the cloud by observing their rate of fall under the action of gravity and computing their radius with the aid of a purely theoretical law known as Stoke's Law. By then dividing the weight of the cloud by the weight of the drops, he obtained a figure for the total number of droplets, and by dividing this number into the total electric charge of the cubic centimeter of gas he obtained the average charge carried by each ion, a figure usually designated by e, for convenience.

DETAILS OF TOWNSEND'S APPARATUS

A diagram of the apparatus used by Townsend is shown in Fig. 76. At the left at A is an electrolytic cell producing oxygen gas at the electrode X. This oxygen is first passed through a solution of potassium iodide in B to remove ozone, and then bubbled through water in the flask C where the ions capture water molecule to form a cloud. This cloud-laden air then passes into a chamber M which is electrically insulated from the earth by paraffin blocks D and H, and which contains tubes E, F, G, containing concentrated sulphuric acid. These are the drying tubes whose function it is to remove the moisture from the cloud. They also remove such part of the charge as is held on ions which in the process of bubbling through E, F, G, have actually touched the sulphuric acid. The dry air containing the rest of the charge next passes into the flask J, the outside of which is covered with tin foil and connected to the electrical connection block K. By means of the latter, the quadrant electrometer L can be connected first to the outside of the flask D and then to the outside of the metal chamber M. The quantity of electricity on the air entering J and also that appearing on M can be measured by noting the deflections in the electrometer per min., as the gas is passing through the system.

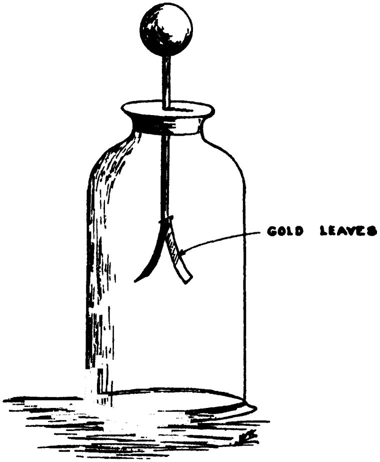

FIG. 75. A SIMPLE GOLD LEAF ELECTROSCOPE
This apparatus consists simply of a glass jar in which is suspended by a metal rod, a pair of gold leaves. When a charged body is touched to the ball at the top the charge is imparted to the gold leaves. When this occurs, the two leaves carrying similar charges will be repelled, causing the leaves to diverge.

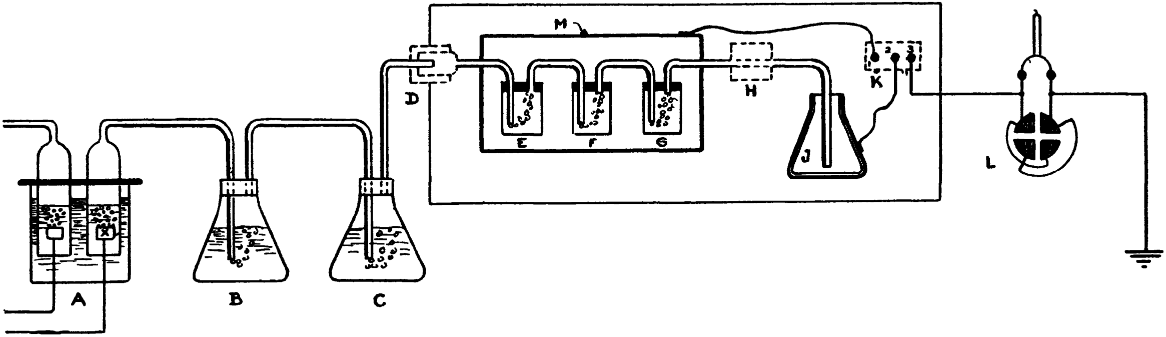

FIG. 76. TOWNSEND'S APPARATUS FOR DETERMINING THE CHARGE OF THE ELECTRON

A. Electrolytic cell producing oxygen. B. Potassium Iodide to remove ozone. C. Water, for production of cloud. D. Paraffin insulator. M. Metal container containing 3 drying tubes E, F, G, filled with sulphuric acid for removing moisture from the gas. H. Paraffin insulator. J. Flask coated on outside with tinfoil to collect electric charge. K. Electrical connection block. L. Quadrant electrometer used for measuring the charge on flask J and metal box M

In this apparatus, Townsend had a means of determining the total charge on the gas, as well as the weight of the cloud formed by passing the charged gas through the water. The quantity of gas entering the system could easily be determined by measuring the current used in producing the oxygen and the electrochemical equivalent of the gas. His method of arriving at the number of droplets in the cloud and the average charge carried by each ion has already been explained.

However ingenious this experiment of Townsend's, it was marked by a number of weak points, all of which combined to introduce errors into the result. In the first place, his assumption that the number of ions is the same as the number of droplets was unfounded. Second, Stoke's law, which he used in weighing the drops, had never been tested experimentally and from a theoretical standpoint this law might be expected to be in error when the droplets were small enough. A third weak point was the assumption that all the droplets in a cloud were of the same size.

Notwithstanding these faults, the experiments of Townsend were of considerable value, for they pointed the way to other methods in which these sources of error were eliminated. Townsend conducted his experiments in 1896. His attempts to determine the value of the charge on the electron were followed by those of Thomson and H. A. Wilson.

Both Thomson and Wilson worked with clouds. Thomson's method had few advantages over Townsend's but Wilson eliminated the awkward assumption that the number of droplets formed is the same as the number of ions and this was a real advance.

None of these methods approached in accuracy and perfection the method later used by Millikan. Wilson obtained for a value of the unit charge on the electron, 3.1×10^{-10} electrostatic units. This was closer than that obtained by previous investigators but was still far from the exact value 4.774×10^{-10} electrostatic units later obtained by Millikan.

The whole history of the evaluation of the charge of the electron is a beautiful example of the development of a method. Here was an entity—a tiny something which we could never hope to see, so small, in fact, a million million of them would find oceans of room on the point of the sharpest needle,—which carried an electric charge; yet gradually a method was evolved whereby this charge was measured with remarkable precision. Millikan's famous oil drop experiment will be described in the next article of this series.

CHAPTER XVII

THE MILLIKAN OIL DROP EXPERIMENT

NO SHERLOCK HOLMES ever exercised more cunning nor laid plans for the capture of his victim with greater certainty than did Robert Millikan plan the final capture of the electron. Long had he been on the trail—long had he studied the habits of his victim and gathered the clues furnished by others but the years so spent proved well worth while. With infinite patience, he had worked out a plan of attack which he knew must be successful. Now the trail narrowed and finally, in the quiet and undisturbed fastnesses of the Ryerson Physical Laboratory at the University of Chicago, the elusive electron surrendered to his relentless pursuer.

No surrender was ever more unconditional—it was complete and carried with it no hidden limitations. Townsend's experiments, we have seen, harbored a number of sources of error which rendered the result extremely uncertain. Millikan's method not only eliminated all the uncertainties of Townsend's method but provided an entirely new way of studying ionization.

MILLIKAN'S METHOD BASED ON WORK OF OTHERS

The work of Townsend and others who attacked the problem, despite the limitations, was not in vain, however, for Millikan's method was derived from the methods of the previous investigators. In modern science, it is rarely that any single man can be credited with all the honors for an important discovery. In scientific research, evolution works just as surely as it does in other natural processes and methods are evolved from the combined efforts of many individuals.

Townsend had shown how to deal with clouds of water vapor. After Townsend, Thompson and H. A. Wilson of the Cavendish Laboratory produced methods in which the downward fall of such clouds could be counteracted by charged plates above the clouds. In other words, a cloud was placed between the two plates of a condenser. When the upper plate was charged, say, with positive electricity, it attracted the negatively charged droplets in the cloud and so arrested their fall. If the charge on the plate was made high enough, the droplets would actually be drawn upward, against the attraction of gravity. Millikan, himself, worked along these lines for a number of years and it was this work which finally led to the conception of his balanced drop method whereby his final successful results were obtained.

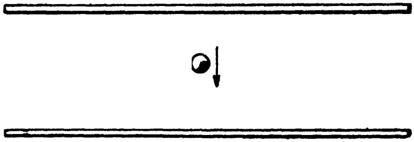

FIG 77 AN OIL DROPLET FALLING IN AIR UNDER THE ACTION OF GRAVITY. ITS RATE OF FALL IS DEPENDENT UPON ITS SIZE AND THE VISCOSITY OF THE AIR THROUGH WHICH IT FALLS

BALANCED DROP METHOD IS SIMPLE

Millikan's method differed from all others in its simplicity and directness. Where others had worked with clouds of droplets, Millikan worked with a single drop.

Suppose that a small single drop of oil, or other substance is placed in the atmosphere between two parallel plates mounted horizontally as shown in Fig. 77. The droplet, obviously, will fall toward the lower plate, due to the attraction of gravity; but, being very small, its rate of fall will be comparatively, slow, due to the viscosity of the air or whatever gas may exist between the plates.

Let us suppose, further, that this droplet carries an electric charge, say a negative charge. Insofar as the action of gravity is concerned, the charge on the droplet will have no effect. It will fall just as fast whether it is charged or whether it is neutral.

If, however, an electric charge is applied to the plates when the charged oil droplet is in the space between, something starts to happen immediately. If the upper plate is given a positive charge (the oil droplet is assumed to carry a negative charge), the droplet will be attracted by the plate and its rate of fall due to gravity will be diminished. If the charge on the plate is increased, the fall of the droplet may be arrested entirely or it may be drawn upward. Two unlike charges, it will be recalled,[1] attract each other with a force that varies directly as the product of the charges.

SPEED OF DROPLET CAN BE CONTROLLED

The speed of the droplet, therefore, can be varied either by varying the charge on the droplet, varying the charge on the plates, or both. If the charge on the upper plate, for instance, is suddenly increased while the charged oil droplet is under observation, a sudden increase in the upward velocity of the droplet will be observed.

If, while the charge on the oil droplet is still negative, the lower plate is given a positive charge, the rate of fall will be greater than that due to gravity alone.

It is obvious that the rate of fall or rise of the droplet can be definitely controlled by varying the charge on the plate.

Suppose, however, that instead of varying the charge on the plates, the charge on the droplet itself is varied.

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[1] Page 54.

In this case also, a change in the rate of motion of the droplet will be observed. If the droplet, already carrying a certain negative charge, acquires a greater negative charge by the capture of a negative ion, the rate of upward motion will be increased. The addition of a still greater negative charge by the capture of a second ion will still further increase the droplet's upward velocity.

If, instead of capturing a negative ion (just how these captures are effected will be explained shortly), the droplet captures a positive ion, the rate of motion will decrease and if it captures another, the speed will still further decrease or its motion may be reversed and the drop will move toward the negative plate. Allowing for the effect of gravity, the direction of motion of the droplet, with respect to the charges on the plates, will indicate whether the droplet carries a positive or negative charge.

Here, then, we have a method for learning something about the charge on the droplet. If the charge on the plates remains constant and the speed of the droplet is suddenly observed to increase or decrease, we may assume that it has in some way acquired a positive or negative charge as the case may be.

HOW THE DROPLETS ACQUIRE CHARGES

A small droplet of this kind may acquire charges in various ways. Usually, if it is formed by atomization by being sprayed from an atomizer, it will acquire a charge by friction. In its rapid passage through the tubes of the atomizer, the scrubbing action may have left it with an excess of negative electrons, giving it a positive charge.

However, the droplet may acquire a charge in another way. It may capture an ion from the atmosphere. In the gases of the atmosphere, there are nearly always some free electrons present. They may be, and are produced naturally, due to radioactive substances in the earth or by the sun or they may be produced artificially by a beam of x-rays or radium rays. Just how they are produced will be described later; here it will be necessary only to assume that these ions are present or that they may be produced.

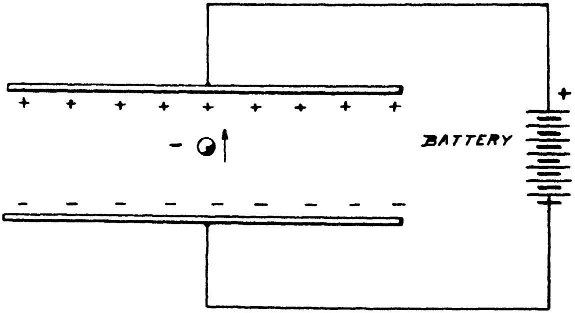

FIG. 78. A NEGATIVELY CHARGED OIL DROPLET BEING DRAWN UPWARD TOWARD THE POSITIVELY CHARGED PLATE, AGAINST THE ATTRACTION OF GRAVITY

In this case, the rate of travel of the droplet depends upon the electric charge on the droplet, and the charge on the plate or rather, the strength of the electric field.

These ions are constantly moving about in the space between the plates and as the oil droplet moves up and down, it is conceivable that occasionally one of these ions will collide with the droplet and be captured by it. The oil droplet, it must be understood, consists of many thousands of atoms most of which are normal; that is, they are satisfied so far as their positive and negative charges are concerned. A small number of the atoms composing this oil droplet, however, may lack an electron or may have an excess of electrons over the required number for satisfaction. It is these unsatisfied atoms which give the oil droplet its charge. If all of its atoms are satisfied, the droplet is said to be neutral and will be unaffected by the charge on the plates. In Fig. 79 is shown a diagram representing an oil drop carrying a single positive charge.

It may not be entirely clear how a droplet carrying, say, a negative charge can acquire a still greater negative charge by the capture of negative ions or electrons. From all we have said, it would seem that an approaching electron would be repelled by the negative charge on the droplet. The explanation lies in the high kinetic energy of the electrons and ions in the atmosphere. This fact was proved experimentally by Millikan. The ion apparently approaches the oil droplet with such speed as to be able to proceed against the repulsive force of the charge on the droplet.

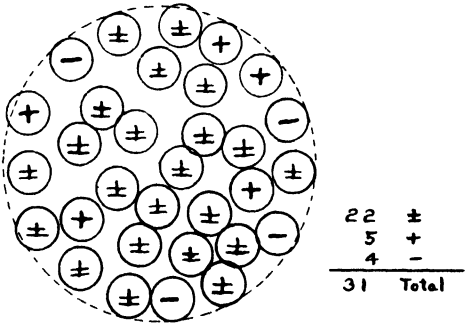

FIG. 79. REPRESENTATION OF AN OIL DROPLET CARRYING A SINGLE POSITIVE ELECTRIC CHARGE

An oil droplet such as Millikan worked with consists of many thousands of neutral atoms, compared to the few that carry a charge. In this diagram is shown a hypothetical oil drop with a total of 31 atoms. Of these, 22 are neutral, 5 carry a positive charge and 4 a negative charge. The net charge, therefore, is positive and in an electric field the drop would tend to move toward the negative plate. If this drop suddenly captured an electron, it would become neutral and it would be attracted only by gravity.

An oil droplet, therefore, may attach to itself either positive or negative ions. A single electron captured by the droplet shown in Fig. 79 would make the droplet neutral.

In his experiments, Millikan was able to control not only the charge on the plates but also, by means of radium rays, the charge on the droplet. Let us see how he went about this.

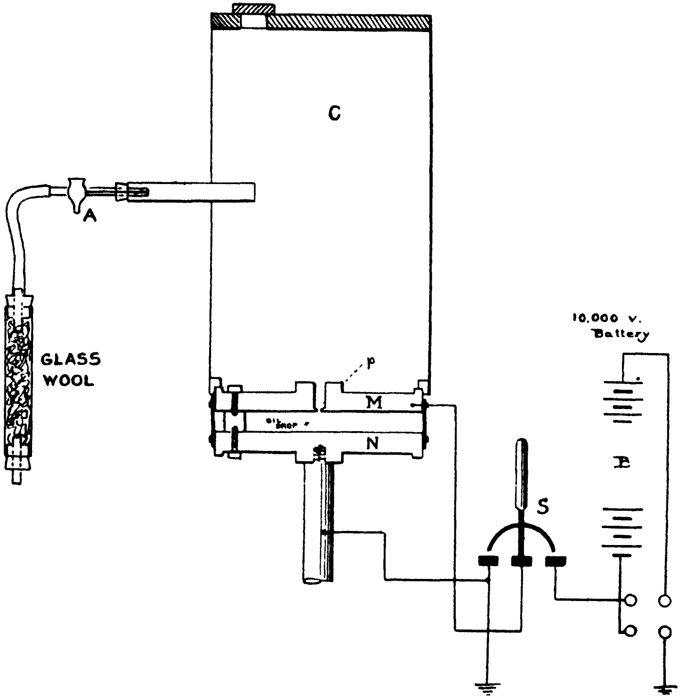

FIG. 80. A SIMPLE DIAGRAM OF MILLIKAN'S APPARATUS

The condenser plates between which the droplet is observed are shown at M and N which are mounted in the lower part of a closed chamber C. An oil spray from atomizer A is introduced into C and as it settles a single droplet will enter the space between the condenser plates M and N through aperture p. A 10,000-v. battery is provided for charging the plates by means of switch S.

DETAILS OF MILLIKAN'S EXPERIMENT

A simple diagram of his apparatus is shown in Fig. 80. The plates between which the oil droplet is floated are designated M and N. An aperture, p, in the center of the upper plate connects with a chamber, C, into which an oil spray is blown from an atomizer A. The air with which this spray is produced is first rendered dust free by passing it through a tube containing glass wool. At B is a 10,000-v. storage battery, so arranged that by means of the switch, s, a positive or negative charge can be imparted to either of the plates or by throwing the switch to the left, the plates can be short-circuited, thus discharging them.

When a spray of atomized oil is blown into the chamber, C, the droplets constituting the spray will slowly fall and occasionally one of them will find its way through the aperture, p, into the space between the plates M and N. When this occurs, the aperture, p, is closed by means of a shutter.

To render visible the droplet of oil which has passed through the aperture, it is illuminated by a powerful beam of light which passes through a small window in the ebonite strip encircling the space between the plates. Under these conditions, when the droplet is viewed through a telescope, it appears as a bright star against a black background. Its motion between horizontal hair lines in the telescope can thus be easily observed and its rate measured by means of a stop watch or chronograph.

In performing the experiment, it was found that the droplets which were captured were quite strongly charged by the friction involved in atomizing the oil. As the droplet (which has a radius of about 1/25,000 of an inch) passes through the aperture, p, it is first allowed to fall toward the plate N under the attraction of gravity. Just before it touched the lower plate, the switch was thrown, charging the upper plate with electricity opposite in polarity to that carried by the droplet. In the field thus created, the droplet moves upward and just before it touches the upper plate or when it crosses the upper hairline in the observing telescope, the battery is disconnected and the plates short-circuited, thus removing the field. The droplet again falls and when it nears the bottom plate, the switch is again closed and the process repeated.

SPEED OF DROPLET VARIED BY BATTERY

By adjusting the voltage of the battery, the speed of the drop could be regulated to any desired degree. The droplet could be made to move up or down at will or could be held stationary in space like Mohammed's coffin.

The downward speed of the droplet due to gravity is always the same regardless of the value of the charge. With a certain field strength, the rate of upward motion will depend upon the charge on the droplet.

When Millikan first made this experiment, the droplet captured an ion from the atmosphere within a few minutes. This was signaled to the observer by a sudden change in speed when it moved upward with the field on. Now, the experiment consisted entirely in observing and noting the ratio between the various rates of speed as the droplet captured or lost ions.

In the accompanying table[2] are shown the results of one of Millikan's early experiments in which the time was determined by means of a stop watch. In this case, the distance between the cross hairs on the telescope corresponded to an actual fall of the droplet of 0.5222 cm.

In Table I, the left-hand column, gives the time (in seconds) of fall due to gravity. In the right-hand column, is given the time required for the droplet to rise from the lower to the upper cross hair.

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[2] Millikan, The Electron, p. 67.

It will be noted that the times required for the droplet to fall under gravity are all alike within the limits of error of stop watch measurements. The time require for the droplet to rise varies, however, The time for the first two trip are alike. With the third, however, the time increased from 12.4 to 21.8, indicating the capture of a negative ion, since in this case the drop was positive. The next trip another negative ion was caught for the time changed to 34.8 and then on the fifth trip with another capture the time became 84.5. This charge was held for two trips and then on the seventh trip, the droplet captured a positive ion for the time decreased to 34.6. The positive ion apparently was of exactly the same value as the negative ion captured on the fifth trip since the charge on the droplet is the same as before.

TABLE I. TIME DATA FROM MILLIKAN'S EXPERIMENT

	Time of fall due to gravity	Time of rise in electric field
	13.6	12.5
	13.8	12.4
	13.4	21.8
	13.4	34.8
	13.6	84.5
	13.6	85.5
	13.7	34.6
	13.5	34.8
	13.5	16.0
	13.8	34.8
	13.7	34.6
	13.8	21.9
	13.6	
	13.5	
	13.4	
	13.8	
	13.4	
Mean	13.595	

Having these times of passage, to find the speed in centimeters per sec. it is merely necessary to divide the total distance of movement 0.5222 cm. by the time required to make the passage. For the first trip, therefore the speed will be $0.5222 \div 12.45 = 0.04196$ cm. per sec.

Now in order to make use of this experiment in explaining the properties of the electron, it is necessary only to make one assumption and that is, *that the velocity of the droplet is proportional to the force acting upon it.*[3] The assumption, however, is subject to a delicate experimental test but here we need regard it only as an assumption.

To obtain a comparative measure of the force acting upon the droplet with different velocities, we need only calculate the difference in velocity between the successive changes in speed. From the table, the first two trip it will be noted gave a speed of 0.04196 cm. per sec. ($0.5222 \div 12.45$). The third trip which was made in 21.8 sec. gives a speed of $0.5222 \div 21.8 = 0.02390$. The difference between these successive speeds is $0.04196 - 0.02390 = 0.01806$.

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[3] If e is the value of the charge on the droplet; m, its mass; v_1, its velocity under gravity g, alone; v_2 its velocity in an electric field x, we have the relation

$$\frac{v_1}{v_2} = \frac{mg}{xe - mg}$$

from which

$$e = \frac{mg}{xv_1}(v_1 + v_2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

If, now, by capture of an ion, the drop changes its charge from e to e′ we may denote the new velocity corresponding to this charge as v_3. Then, from equation I, the value of the captured charge e″ is

$$e'' = e' - e = \frac{mg}{xv_1}(v_3 - v_2)$$

Since $\frac{mg}{xv_1}$ is a constant for the drop, any charge which it captures will always be proportional to $v_3 - v_2$. In other words, it will be proportional to the change produced in the velocity by the captured ion.

In the same manner, Millikan calculated the differences for each of the speed changes shown in the right-hand column of Table I, as follows:

TABLE II. DIFFERENCES FOR SPEED CHANGES OF TABLE I

Observed Velocities	Difference in Velocities
0.5222 ÷ 12.4 = 0.04196	
	0.01806
0.5222 ÷ 21.8 = 0.02390	
	0.00885
0.5222 ÷ 34.7 = 0.01505	
	0.00891
0.5222 ÷ 85.0 = 0.006144	
	0.00891
0.5222 ÷ 37.7 = 0.01505	
	0.01759
0.5222 ÷ 16.0 = 0.03264	
	0.01759
0.5222 ÷ 34.7 = 0.01505	
	0.00891
0.5222 ÷ 21.8 = 0.02390	

Even in the preliminary experiments, it was apparent from a study of the values given at the right of the above table that a simple relation existed between these numbers representing the differences in velocities. They are all integral multiples of some unit. Thus,

0.01806 = 2 × 0.00903
0.00885 = 1 × 0.00885
0.00891 = 1 × 0.00891
0.00891 = 1 × 0.00891
0.01759 = 2 × 0.00880
0.01759 = 2 × 0.00880
0.00891 = 1 × 0.00891

These values within the limits of stop watch measurement, it will be noted, are all alike. Much more regular results were obtained in later experiments in which a chronograph was used to determine velocities.

Starting with a drop of, say, 100 charges, Millikan varied the charge to, say, 10 and found that every variation was an integral multiple of one unit. Finally, on reducing the charge still further, he found that this unit also was two or three times the same unit, thus showing that the charge originally given to the drop by friction as it passed through the atomizer was also built up of "atoms of electricity."

These relationships, throughout the years that they have been observed by Millikan and others, have been found to hold absolutely without exception, no matter in what gas the droplets have been suspended nor of what material they were composed. Millikan has held a given drop under observation for five or six hours at a time and during this time the droplet has been observed to capture not six or ten ions but hundreds of them. In Millikan's own words,[4] "Indeed, I have observed, all told, the capture of many thousands of ions in this way and in no case have I ever found one, the charge of which, when tested as described, did not have exactly the value of the smallest charge ever captured or else a very small multiple of that value. Here, then, is direct, unimpeachable proof that the electron is not a 'statistical mean' but that rather the electrical charges found on ions all have either exactly the same value or else a very small multiple of that value."

As explained in earlier articles of this series, long before Millikan's work, physicists had been confident that electricity was atomic but in Millikan's experiment they were furnished with absolute and incontrovertible proof.

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[4] Millikan, The Electron, p. 70.

And by such beautifully simple means. Who would have thought it possible to devise a method so simple and direct that it could have been used a century ago, which proved the atomic nature of electricity to within 1 part in 1000? This gives us the answer to the question which we asked in Chapter XV, "What, after all, have we to prove that the electron really exists?" Beyond all question, electricity, by Millikan's experiment, is shown to be made of tiny specks which are all alike. Here we have outlined the method without regard to refinements. Later, Millikan performed the experiments with greater accuracy and while his results were more accurate, his original conclusions remained unchanged.

CHAPTER XVIII

THE NUMERICAL VALUE OF THE ELECTRONIC CHARGE

BEFORE LEAVING our discussion of Millikan's discovery of the electron started in the previous article, it will be of interest briefly to consider the work which came as the immediate consequence of his balanced drop experiments. For it must be understood that these experiments are of tremendous importance not only in the field of electrical research but in all other sciences as well. So far, in describing Millikan's work, we have but shown that electricity is atomic—that it consists of particles, just as matter is known to consist of particles, the atoms and molecules. What was of even greater importance to Millikan, however, was to determine the exact value of the electric charge carried by the electron.

The way for doing this seemed clear. The balanced drop experiment showed that with a given droplet in a given field, there was a different rate of speed for each charge that the droplet carried. To convert these speed units into electrical terms, it was necessary only to know how, in a given medium (air in this case) the speed due to the charge on a drop was related to the size of the drop.

This relation between the velocity of the drop and its size, it was known could be determined by the aid of Stokes law. In applying this law, however, Millikan found that for extremely small droplets, Stokes law was inaccurate. So steps had to be taken to determine just where, as the size of a large droplet was reduced, Stokes' law becomes invalid, and what measures must be applied to insure correct results when it was used with small droplets.

How this was accomplished,—the care which was exercised in insuring accuracy, the painstaking work done in determining the exact coefficient of the viscosity of air (which was a factor to be known) is a story of absorbing interest and the reader who wishes to know the details is referred to Millikan's book, The Electron.[1] An incidental part of this work was the weighing of the droplet. It was apparent that if the weight of the oil drop was known, the charge on the drop could be easily determined. Under gravity, the velocity of the drop is proportional to its weight but in an electric field, the velocity is proportional to the charge which it carries. Since both of these velocities could be measured directly, it was evident that the weight or the charge could be determined if either one of these factors were known.

WEIGHING TO THE TEN BILLIONTH OF A MILLIGRAM

The charge was found with the aid of Stokes' law. What was done, therefore, was simply to charge a drop with a given number of electrons and then pull it up against gravity by the electric field or it was kept stationary and balanced against gravity in the manner already described. In this way, Millikan provided an electric balance in place of a mechanical one, so sensitive that it would weigh accurately and easily to *one ten billionth of a milligram!* A milligram is less than 1/28,000 of an ounce.

Such an electric balance makes it possible to weigh bodies accurately, so small as not to be visible to the naked eye. "For," using Millikan's own words, "it is only necessary to float such a body in the air, render it visible by reflected light in an ultra microscope arrangement of the sort we were using, charge it electrically by the capture of ions, count the number of electrons on it and then vary the potential applied to the condenser

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[1] The University of Chicago Press.

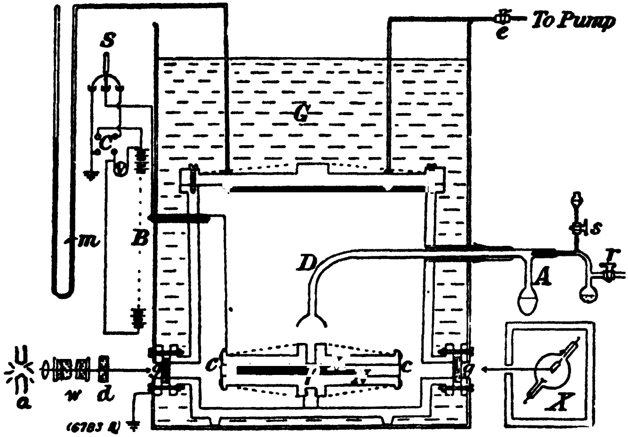


FIG. 81. FINAL SET UP USED IN MILLIKAN'S OIL DROP EXPERIMENT

In this apparatus the oil drop is suspended between the plates M and N. D, in an air tight container into which the oil spray is introduced by atomizer A. To prevent temperature changes, the entire equipment is placed in engine oil in container G. An arc light at a, illuminates the drop through window g and c. At X is an x-ray tube for ionizing the atmosphere between the plates.

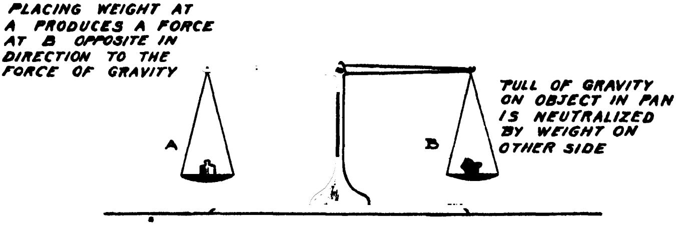
plates, or the charge on the body until its weight is just balanced by the upward pull of the field. The weight of the body is then equal to the product of the known charge by the strength of the field."

DETAILS OF FINAL APPARATUS

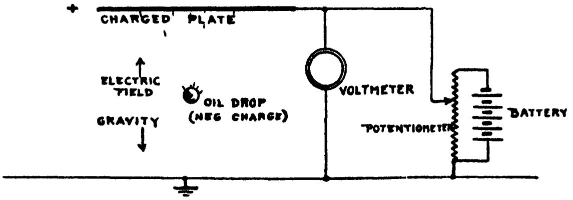
Millikan's final experiments were conducted with great refinement. Figure 81 shows the set-up of the apparatus used in the later experiments. The condenser plates between which the droplets were observed are shown at M, N, mounted at the bottom of a heavy brass vessel D. In these experiments, it was necessary to observe the action of the drop under varying pressures, so a connection was made to exhaust and compression pumps so that the pressure in D could be varied. The pressure was measured by a mercury manometer m. At the left at a is an arc lamp for illuminating the droplet through windows g and c. It is evident that, for the success of this experiment, the air between the plates must be completely stagnant. To insure this, temperature variations must be eliminated, so the entire vessel, D was placed in a constant temperature bath of engine oil which permitted of a temperature variation of not more than 0.002 deg. C. To absorb the heat rays from the arc lamp, the rays were passed first through a water cell 80 cm. long and then through a cupric chloride cell. The atomizer for introducing the oil spray is shown at A. An x-ray tube is shown at the right for ionizing the atmosphere between the plates.

This arrangement, except for the refinements, it will be noted is virtually the same as that shown in the preceding article. Extreme accuracy was observed in every detail. The condenser plates for instance had surfaces which were polished optically and made flat to within two wave lengths of sodium light. The voltage on the plates was determined after each reading in terms of a Weston standard cell and was accurate to one part in 3000.

Let us transport ourselves to the Ryerson laboratory and in our imagination picture what we see in the eyepiece of the microscope. The tiny oil droplet, invisible to the naked eye, blazes forth, a brilliant star against a dark background. As we put our eye to the eyepiece, the drop is rising slowly. We watch it carefully and when it touches the upper cross hair in the field of the microscope we suddenly throw off the field on the plates by means of the switch S. Immediately, the droplet begins to fall and we watch it until it touches the lower cross hair when we again charge the plates by throwing



MECHANICAL BALANCE



ELECTRICAL BALANCE

FIG 82 COMPARISON BETWEEN MECHANICAL AND ELECTRICAL BALANCE

Above is shown a simple mechanical balance In this device the pull of gravity on the object to be weighed in the right hand pan is exactly balanced by the upward pull due to the weight in the left hand pan The beam pivoted at the center serves to reverse the direction of force In the lower diagram is shown an electrical balance Here the potential of the battery is the 'weight" used to balance the gravitational pull on the drop

the switch. The drop starts upward at once but this time it rises much faster than before. Evidently, on its downward journey, it captured an ion carrying a negative charge. (We assume the upper plate to carry a positive charge.) We watch the drop closely and when it again touches the upper hair line, the field is cut off and the time recorded on the chronograph. On the next upward journey, it rises still faster showing the capture of still another negative ion but as the droplet reaches the center of the space between the plates it suddenly slows down again. In this case, it has captured a positive ion, thus neutralizing some of the negative charge which it already carried.

The whole thing is marvelously simple and yet, as we see this brilliant star suddenly accelerate or decelerate as it captures or loses charges, it seems a bit uncanny. We are observing the direct effect of the smallest "thing" in the universe!

By carefully noting the same droplet for a long time and noting the speed each time, we see at once the very simple relation that exists between the speeds. Knowing the law connecting the speed of droplet, its size, and the charge, the charge of the single electron is easily determined.

THE NUMERICAL VALUE OF THE ELECTRON'S CHARGE

Millikan's work extended over a period of years and thousands of observations were made but at no time was a variation observed which could not be accounted for and explained. When all was done and the final calculations were made, the absolute value of the charge of the electron was found to be

$$4.774 \times 10^{-10} \text{ absolute electrostatic units}$$

Now, what does this number mean? Why did Millikan and others spend years upon years, working in laboratories, merely to bring forth this number?

Before explaining it, let us say, here, that this number 4.774×10^{-10} is the most fundamental of all physical or chemical constants. It expresses in terms with which we are familiar, the value, not only of the smallest possible electric charge but also, in a way, the smallest particle of matter.

It represents a quantity of electricity—the smallest quantity of electricity which it is possible to have.

Ordinarily, where we measure electricity we use the ampere or the watt and when we measure its pressure or potential we use the volt. These are, of course, arbitrary units, selected because of their fitness in measuring such quantities of electricity as we deal with. No system of measures is of value, however, unless the units on which it is based can be reproduced. Thus, the meter, which is the standard unit of length in the metric system, was selected as a length equal to the ten millionth part of the northern quadrant of the earth. In this same system, the unit of mass is derived from the unit of length and is the gram, which is the mass of a cubic centimeter of water at 0 deg. Centigrade.

A number of systems of fundamental units have been proposed from time to time, some of which have been used to a greater or less extent. The system on which our electrical units are based is the centimeter-gram-second system, usually called the CGS system and based on the centimeter, the gram and the mean solar second.

In this system, the unit of electric current is the absampere. This represents an amount of current the value of which is such that when one centimeter length of the circuit is bent into an arc of one centimeter radius, the current in it will exert a force of one dyne on a magnet pole of unit strength placed at the center of the arc. The dyne referred to in this definition is the unit of force in the C.G.S. system. This represents the force which after acting on a free gram during 1 sec. creates in that mass a velocity of 1 cm. per sec. Thus it is seen that a unit of current can be derived from the fundamental units of length, mass and time. It is expressed in terms of the magnetic field it produces.

For practical purposes, the C.G.S. units of electricity and magnetism are either too small or too large, so a system of practical units has been developed. The ampere is our practical unit of current and is one-tenth of the absampere.

From the ampere, we get our practical unit of electric quantity. This is the coulomb, and it is defined as the quantity of electricity to be conveyed by one ampere in one sec. The ampere, in other words, represents the transfer of a coulomb per sec. The coulomb represents a unit of quantity just as a gallon in hydraulics represents a unit of quantity.

THE ELECTRON IN TERMS OF THE COULOMB

Now, the charge carried by the electron also represents a definite amount of electricity—it in itself is a unit of quantity. How then, does the charge on the electron, which we have said is 4.774×10^{-10} electrostatic units, compare with the coulomb?

The coulomb is the practical unit of quantity. The absolute unit of quantity in the C.G.S. system is very much smaller than the coulomb, millions of times smaller in fact. Its value is expressed as 3.3×10^{10} coulomb.

To find out, therefore, just how the electron compares with the coulomb, we multiply

$$\begin{array}{rl} & 4.774 \times 10^{-10} \\ \text{by} & \underline{3.333 \times 10^{-10}} \\ \text{and obtain} & 1.591 \times 10^{-19} \end{array}$$

In other words, the value of the charge on the electron is $\dfrac{1.591}{10{,}000{,}000{,}000{,}000{,}000{,}000}$ of a coulomb, or there are 6,280,000,000,000,000,000 electrons in a coulomb.

Since an ampere is a coulomb per second, it is evident that a current of one ampere in an electric circuit means simply that six billion, billion electrons pass a given point in the circuit every second.

Numbers such as these mean very little to the ordinary mind. Whether the above strings of figures have 15 ciphers back of the integer or 19 of them, is of little significance to us. We can form no mental picture of 6 billion, billion electrons simply because such numbers are entirely beyond our experience. The best we can do is to compare them with experiences with which we are familiar.

Suppose, for instance, we set out to count the electrons which entered a condenser during one second with a current of one ampere; that is, the number of electrons in one coulomb. To facilitate the process, we devise a counting machine which counts one thousand electrons per second. To count the 6 billion billion electrons which have entered the condenser in that one second would require that this counting machine count at the rate of 1000 per sec., uninterruptedly for 190 million years! This, perhaps, is equally inconceivable, still it is interesting and provides us with a little food for thought.

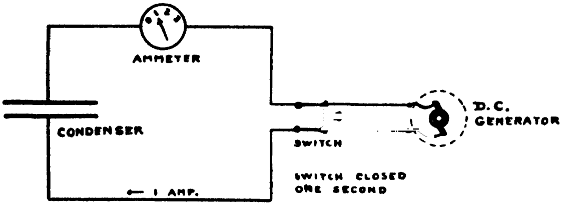


FIG. 83. DIAGRAM TO SHOW VALUE OF A COULOMB

If the switch in this circuit is closed for just one second, and if during that second, a steady current of one ampere flows into the condenser, there will, at the end of that second be stored up in the condenser exactly, one coulomb of electricity. This means that over 6 billion billion electrons have entered the condenser.

So, in the electron, despite the fact that we have several systems of units, we have the natural unit of electricity, one that has no relation with anything else.

It is more than that, however; it is, without doubt, the most fundamental unit in the universe, for, as has been explained in previous articles of this series, all matter is made up of these electrons. Millikan experimented, for many years, with all sizes of drops of various materials and in various gases, but in no case has there ever been a variation from the absolute quantity 4.774×10^{-10} electrostatic units for the charge. No matter from what material the electron is obtained or in what manner, it is always the same.

The science of electricity was already well developed when the electron was discovered and the laws of its action determined. If the value of the electron's charge had been known earlier, it is probable that today we should have an entirely different system of practical units based directly on the electron. It is unfortunate that this is not the case. We have already discussed[2] the discrepancy between the known direction of flow of electrons and our common conception of the direction of current in a circuit. The electron flow we know is directly opposite to the direction in which we say the current flows and as a consequence we are compelled to make awkward compromises. There is no such thing as a flow of electrons against the current. The current is from negative to positive and *not* from positive to negative as we are taught.

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[2] Page 81.

CHAPTER XIX

PRINCIPLES OF THERMIONIC EMISSION

HAVING CONSIDERED the method by which the electron was isolated and measured and having learned something about the fundamental relation of the electron to simple electrical phenomena, we are now in a position to turn our attention to an extremely interesting phenomenon which has been put to great practical use in recent years. This phenomenon is intimately concerned with the action of the electron and although it was first noticed many years ago, it was not until a definite knowledge of the electron was available that its true nature was understood.

Some 45 yr. ago, long before anybody knew anything definite about electrons, Thomas Edison, in developing the incandescent lamp noticed a curious phenomenon which occurred when he placed a small metal plate in the bulb of a lamp in the manner shown in Fig. 84. When the filament became incandescent, Edison found that the plate became charged electrically and if it was connected through a sensitive galvanometer to the positive terminal of the filament, a current would flow. When the plate was connected to the negative terminal of the filament, however, no current would flow. Apparently, the presence of the hot filament in some mysterious way contributed to produce a charge on the plate. This charge was negative, since it left the plate when the latter was connected to the positive terminal of the filament.

That hot bodies produced electrical effects had been known before; indeed, for over a hundred years, it had been known that when a metal is brought to a state of incandescence, the air in its immediate neighborhood becomes a conductor of electricity. At the time Edison noticed the effect, it was considered a curious phenomenon but it could not be explained and for a time nothing resulted from it. It became known as the Edison effect and was forgotten.

FURTHER ASPECTS OF METALLIC CONDUCTION

With this introduction, let us leave this phenomenon for the present and review briefly the theory of electric conduction in solids discussed in an earlier chapter.[1] It was shown that conduction in solids is due to the interchange of so-called free electrons between the atomic systems of the metals. These electrons have no permanent family ties—they are a restless lot, wanderers who lodge for a time with one atomic family and then becoming restless or bored perhaps, move on to another atomic system.

Compared to the total number of electrons comprising the atomic systems of a metal, these free electrons are only few in number, yet in terms with which we are familiar they are exceedingly numerous. In ordinary metals, the density of these free electrons is approximately 16,000 coulombs per cubic centimeter. A coulomb, it will be recalled, contained over six billion billion electrons, so a cubic centimeter of metal contains about one hundred thousand, billion, billion free electrons!

These free electrons are in constant motion and are continually colliding with one another and with the atoms and molecules of the metal which are also in motion. Temperature, it has been shown, is merely the manifestation of molecular agitation; the greater the velocity of the molecules of a substance and the greater the number of collisions between them, the higher is the temperature of the substance. The free electrons share the motion of the atoms and molecules. The individual

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[1] Page 38.

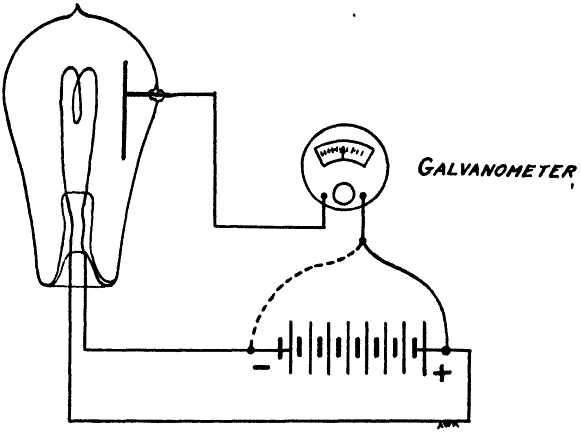

FIG. 84. THE EDISON EFFECT

If the plate is connected, through the galvanometer, to the positive terminal of the filament a current will flow while if the connection is made to the negative terminal no current flows.

velocities of the electrons and atoms at any instant differ widely but their velocity as a whole gives an average velocity which is determined by the temperature of the metal. Due to their comparatively small mass, the average velocity of the free electrons is very much greater than the average velocity of the atoms and molecules.

Because of the frequency of collisions of the atoms in a metal, a large number of electrons can be made to move in a definite direction under the influence of comparatively low values of electromotive force. Thus an electric current is produced in the metal. This action has been fully described.

WHAT KEEPS THE ELECTRONS IN THE METAL

Now, a question arises. If it is true, as we know it is, that these electrons are moving about so rapidly, why do they not escape from the metal in which they are active? They possess considerable kinetic energy and it would seem that, so endowed, those near the surface of the metal might actually fly clear of the metal and leave it. The natural answer to this question is, of course, to assume that there exists at the surface of the metal a restraining force which tends to keep the electrons within the substance. Such an assumption was made by O. W. Richardson in 1901 and since it was an assumption, it was not the most satisfactory answer but developments which have taken place since then have shown that Richardson's assumption was one which has not led us astray. Recent developments in the theory of atomic structure compel us to believe that such a restraining force must necessarily exist at the surface of substances. In order for an electron to escape from a substance, therefore, it would have to have an amount of kinetic energy sufficient to overcome the restraining force or surface tension of the substance.

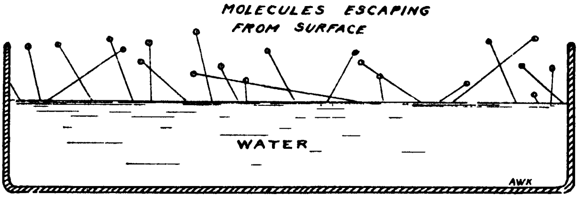

FIG 85 DIAGRAM TO ILLUSTRATE THE EVAPORATION OF WATER

The molecules near the surface which acquire sufficient velocity are able to overcome the surface tension of the liquid and are projected into the atmosphere or space beyond.

EVAPORATION OF WATER

A better understanding of this subject may be had if we consider the process of evaporation of water. It is common knowledge that when a vessel of water is exposed to the atmosphere at ordinary temperatures, evaporation takes place and that in time the entire mass of water will have been converted into water vapor. This process of evaporation can be accelerated by heating the water. If it is heated to a sufficiently high temperature the rate of evaporation becomes very great and boiling results.

This process of evaporation is due to the thermal agitation of the water molecules. As heat is applied to a vessel of water, the velocities of the molecules increase and the frequency of collision between the molecular systems also increases. Due to the severe impact of collisions, certain of the molecules attain velocities much greater than that of the average. If the molecules which have thus acquired velocities greater than the average happen to be near the surface of the liquid, they may overcome the surface tension of the liquid and be projected out into the atmosphere above the surface of the liquid. Thus they become gas or vapor molecules.

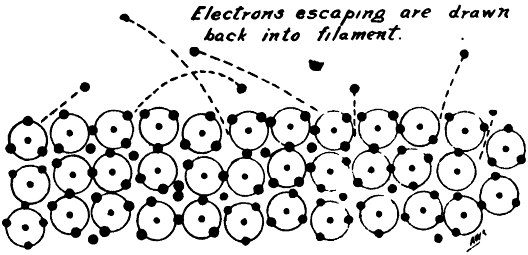

FIG. 86. SHOWING THE "EVAPORATION" OF ELECTRONS FROM A HOT METAL

Known commonly as thermionic emission, this phenomenon is similar to the evaporation of water. The thermal agitation of the molecular structure of the metal provides the free electron with sufficient velocity to escape from the metal. The loss of a number of electrons in this manner leaves the hot metal with a positive charge, which acting upon the electrons draws them back into the metal.

As the temperature of the liquid is raised, the average velocity of the molecules becomes greater and more molecules attain velocities great enough to carry them out of the liquid.

What is true of water in this respect is true also of other substances such as metals. The molecules and

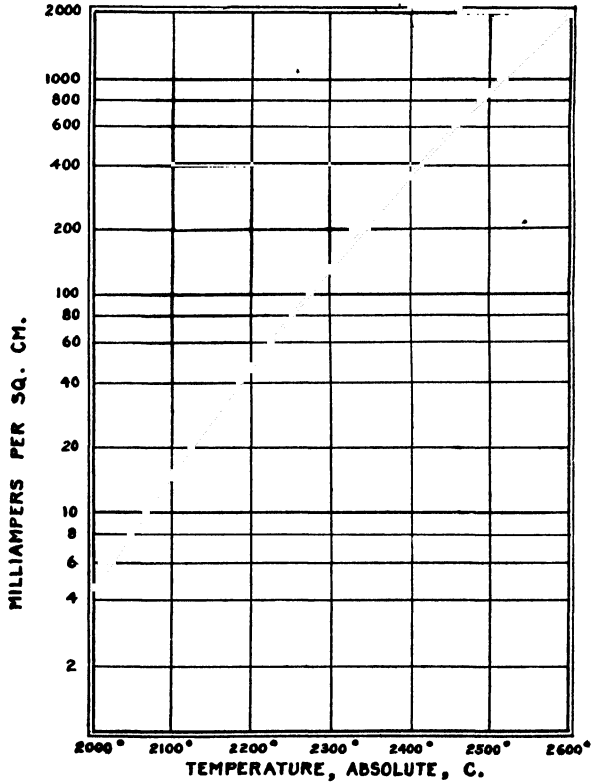

FIG. 87. GRAPH, SHOWING HOW THE ELECTRON EMISSION FROM TUNGSTEN VARIES WITH TEMPERATURE

In this case the electron emission is given in milliamperes. The number of electrons actually emitted can be obtained by merely multiplying the number of milliamperes by 6,280,000,000,000,000.

atoms of metals when heated to high enough temperatures also attain velocities sufficiently high to enable them to escape from the surface of the body, thus resulting in evaporation of the metal. The number of atoms thus liberated or what is the same thing, the rate of evaporation, depends upon the temperature and the latent heat of the particular metal under consideration. Of course evaporation of metals occurs at temperatures very much higher than that of water but the principle involved is the same.

EVAPORATION OF ELECTRONS

Now, it is logical to suppose that if atoms are able to acquire sufficient velocity to overcome the surface tension at the surface of a metal, the free electrons also might be able to do the same thing.

This actually is what occurs. At high temperatures, the molecular activity of both the atoms and free electrons is greatly increased and certain of the free electrons acquire sufficient velocity to enable them to overcome the restraining force at the surface and they are thus projected out into space. As early as 1899, J. J. Thomson had shown that negative electricity was given off from the hot filament of Edison's lamp in the form of electrons but the mechanism of this emission was not known until O. W. Richardson, in 1901, showed that the electrons are emitted solely by virtue of their kinetic energy.

The action is very much like that of the evaporation of water which we have described. The free electrons in a metal behave much like the molecules of a gas; that is, they move about at velocities which depend upon the temperature of the metal. At ordinary temperatures very few electrons in the more common metals possess sufficient kinetic energy to overcome the surface tension at the boundaries of the body and the number of electrons escaping at such temperature is negligibly small.

At any particular moment, some electrons will have zero velocity while others will have extremely high velocity. The majority, however, will have velocities ranging between the two extreme values of speed. It is only those few electrons with the extremely high velocities that are able to escape through the surface.

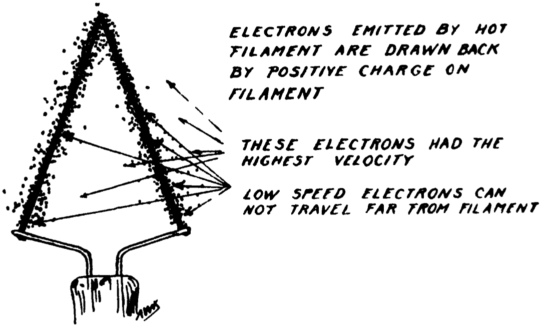
ELECTRONS EMITTED BY HOT FILAMENT ARE DRAWN BACK BY POSITIVE CHARGE ON FILAMENT
THESE ELECTRONS HAD THE HIGHEST VELOCITY
LOW SPEED ELECTRONS CAN NOT TRAVEL FAR FROM FILAMENT

FIG 88 SHOWING THE EFFECT OF THE FILAMENT UPON THE ELECTRONS

After an electron has escaped from the filament by virtue of its kinetic energy, the filament is left with a positive charge and the electron is drawn back into the filament again Thus, a swarm of electrons remains in the vicinity of the filament which decreases in density with increase of distance from the filament Only the highest velocity electrons ever reach the outer layer of this electron swarm

The evaporation of electrons from metals occurs at a lower temperature than that at which evaporation of atoms occurs. This is due to the fact that the average velocity of the electrons is much higher than that of the atoms. Naturally, therefore, we would expect to obtain a copious emission of electrons at a temperature considerably lower than the boiling point of the metal and such is the case. Figure 87 shows how the electron emission from tungsten varies with temperature.

PHENOMENON IS BASIS OF MANY DEVELOPMENTS

The phenomena, at first regarded merely as an interesting fact, is responsible for some of the most startling developments in the realm of electricity, for it is the foundation of the modern radio industry. Without electron emission from hot filaments, there would be no radio vacuum tubes and without vacuum tubes there would be no radio broadcasting and receiving as we know it today. From this it should not be inferred, however, that the vacuum tube is absolutely essential to the production of radio waves, but by its use the production of these waves is so simplified that its advent has revolutionized the art of radio.

Electron emission also plays a major part in other developments, such as the x-ray, the cathode ray oscillograph, and alternating current rectifiers. Transcontinental telephony is made possible because of it. Before discussing these applications, however, it will be necessary to study more in detail, the further consequences of this electron evaporation from hot metal surfaces.

While the chart in Fig. 87 showing the theoretical electron emission indicates that great numbers of electrons are emitted at a temperature well below the melting point of tungsten[2] in an ordinary lamp, for instance, no such numbers are emitted. This is due to the fact that the electrons thrown out are drawn almost immediately back into the filament again. When an electron leaves the surface of the filament, the latter is left with a positive charge and so attracts the escaping electron. There are, therefore, almost as many electrons falling back into the filament as are expelled.

Suppose, however, that in addition to the filament there is inserted into the bulb a small metal plate such as Edison used and that this plate is given a positive charge by connecting it with the positive terminal of the lamp filament. Thus an electrostatic field will be established between the filament and the metal plate. Under these conditions an electron when it has been ejected from the filament will be acted upon by a combination of forces, one tending to draw it back towards the filament and another tending to draw it to the positively charged plate; the strongest force, naturally, will draw the electron towards it. So, by impressing a high enough positive potential on the plate, it will be possible to draw the electrons away from the filament

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[2] 3400 deg. C.

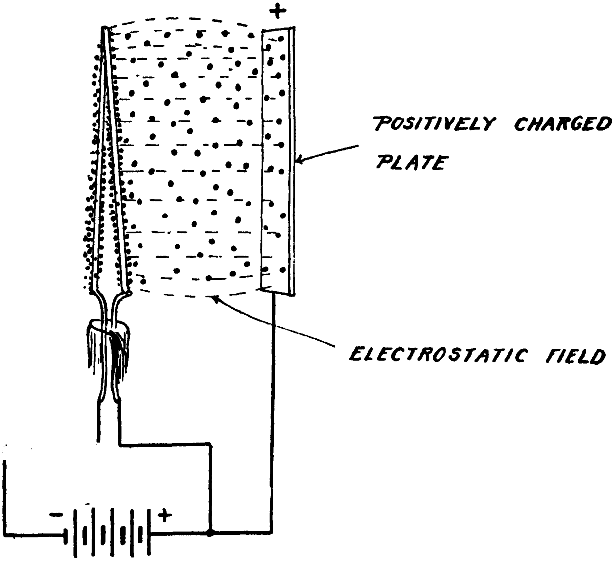

FIG. 89. THE EFFECT OF A POSITIVELY CHARGED PLATE UPON THE ELECTRON

With this arrangement, the electrons, after being expelled are acted upon by the electrostatic field between the plate and the filament and as a consequence are drawn toward the former.

toward the plate just as fast as they are emitted by the former. In this manner, a current is established which flows from the hot filament to the plate, through the external circuit to the positive pole of the battery, and through the battery to the negative terminal of the filament.

In this case, the battery furnishing the energy to create the electric field is the same as that used to light the filament but if desired a separate battery could be used as shown in Fig. 90. Usually, if it is desired to remove all the electrons being emitted from the filament, a separate battery is necessary since a higher potential is required than can be supplied by the filament lighting battery.

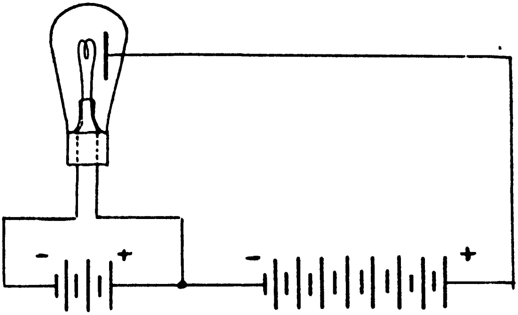

FIG. 90. ANOTHER METHOD OF CONTROLLING THE ELECTRON CURRENT

In this case a separate battery is used to establish the field between the filament and the plate.

As might be expected, the number of electrons which leave the filament is affected by the atmosphere in the bulb. If there is gas in the bulb, the electrons leaving the surface of the filament can not travel far without colliding with the heavy atoms of the gases. For this reason, the emission can be facilitated by exhausting the gases from the bulb so that only a very low pressure remains. In a perfect vacuum, the electrons would encounter no heavy gas molecules and their progress would be unimpeded.

Here, then, we have a new method of producing electric conduction in gases or even in a perfect vacuum. In Chapter VI of this series of articles, we showed how an electron current was established by the presence of free electrons or ions in the space between two oppositely charged plates. In the chapter on insulators and conductors it was shown also that if the potential gradient through a dielectric is made high enough, a current will be established due to the rupture of the normal atoms into positive and negative components. Now, however, in the phenomenon we have just described we have at our disposal a more effective method of producing conduction through gases, for it is seen that by means of a hot filament or other form of cathode an electron current can be produced by boiling out, so to speak, the electrons in the filament itself.

These currents produced by incandescent cathodes have come to be known as thermionic currents, since the emission is the result of thermal agitation of the molecular structure of the cathode.

Since this study of thermionics deals directly with the electron in its "raw" state, it will be of considerable interest to discuss some of the more common applications of this principle in subsequent chapters.

CHAPTER XX

THE TWO ELECTRODE VACUUM TUBE

FROM THE EXPLANATION of the principles involved in the emission of electrons from a hot cathode, it is evident that this phenomenon serves to explain the Edison effect referred to at the beginning of the preceding chapter. It will be recalled that when the plate in Edison's lamp was connected to the positive terminal of the filament, the galvanometer in the circuit indicated an electric current. This current, we know now, is the result of electron emission from the hot filament of the lamp. When the plate was connected to the positive terminal of the filament battery, the plate became charged positively and an electrostatic field was established in the space between the filament and the plate so that any electrons in this space would, under the action of this field, tend to move to the positive plate. Thus there is established a space current which will be indicated by a galvanometer connected into the pate circuit. So what remained an insoluble mystery to Edison in the early eighties is now perfectly clear because of our knowledge of the electron.

If the plate in the bulb, instead of being connected to the positive terminal of the battery is connected to the negative terminal, the plate will assume the same potential as the filament so that there will be no electrostatic field to draw electrons to it. Under these conditions practically no electrons are carried to the plate and no current flows.

HOW A VACUUM TUBE RECTIFIES ALTERNATING CURRENT

A device of this kind incorporating a hot filament or cathode and a cold anode or positively charged plate, therefore possesses the property of what is known in

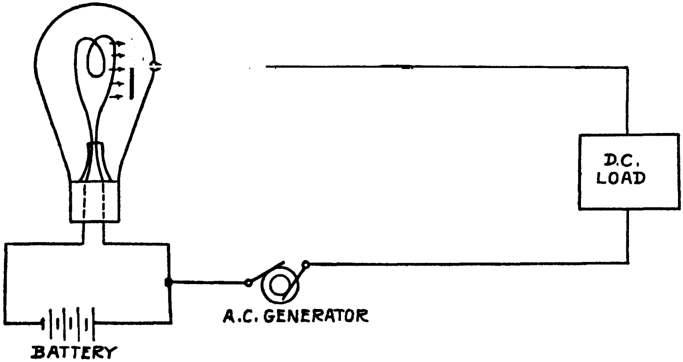

FIG. 91. SHOWING HOW A TUBE RECTIFIES AN ALTERNATING CURRENT

The thermionic principle permits the current to flow from the filament to the plate but not from the plate to the filament. Hence, an alternating current tending to flow in the circuit will have one-half of the cycle suppressed, causing a pulsating direct current to flow in the circuit.

electrical engineering as unilateral conduction. In other words, such a device is capable of conducting current if it flows in one direction but not in the reverse direction. The action is very much like that in a non-return valve, and as such, a tube of this kind will serve as a rectifier of alternating current.

Suppose that the device is connected into an alternating current circuit in the manner shown in Fig. 91. Since alternating potential is impressed across the space between the filament and plate, an alternating electrostatic field will be set up between these elements, the frequency of which will be equal to the frequency produced by the generator. The potential on the plate will vary continually from positive to negative and back again. Whenever the plate is charged positively, current will flow from the filament to the plate, but when the plate polarity changes to negative in the succeeding half of the cycle, the electrons are all driven back into the filament and no current flows. Thus the introduction of the tube in the alternating current circuit has the effect of suppressing the negative half of the cycle as shown in Fig. 92. The resulting effect is a pulsating direct current as shown at B. The positive loop is somewhat distorted because of the way in which the resistance of the tube varies with the current. A pulsating current of this character can be used for charging storage batteries and in this field, such vacuum tube rectifiers have received great application. The Tungar and Rectigon battery chargers so well known to radio fans employ rectifying elements of this type.

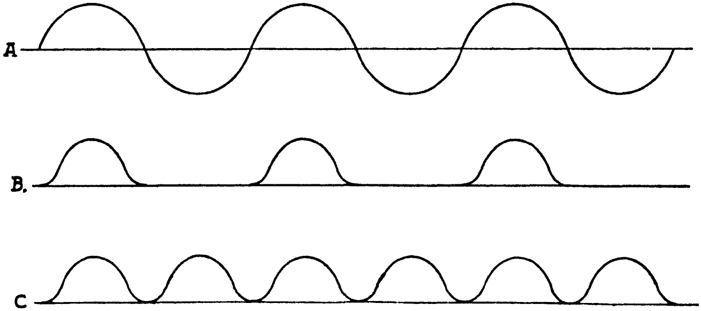

FIG. 92. WAVE DIAGRAMS SHOWING EFFECT OF HALF AND FULL WAVE RECTIFICATION

A showing a simple alternating current wave. B shows the effect of a single rectifying tube in the circuit. C shows full wave rectification, obtained by the use of two tubes connected as shown in Fig. 3.

This rectifying principle of the two-element or two-electrode vacuum tube was first recognized in 1905 by John A. Fleming in England.[1] At that time, Fleming was engaged in the development of a system of wireless telegraphy and he obtained a patent on the use of the vacuum tube as a detector of high frequency electrical oscillations. This patent[2] became one of the fundamental patents in vacuum tube development.

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[1] J. A. Fleming, Proc. Royal Society, Jan., 1905.

The arrangement described above, merely suppresses one-half of the alternating-current wave. The effect is the same that would be obtained by merely opening and closing a switch in an alternating-current circuit so that the circuit was completed only when the current flowed, say, in the positive direction. By an arrangement of two tubes or by means of a modified form of tube employing two plates, both halves of the cycle may be utilized. The arrangement for accomplishing this is shown in Fig. 93. Although two tubes are used, only one tube is in use at one time. A little study of the diagram will show that while the plate of one tube is charged positively the plate in the other tube is charged negatively; thus, while one tube is conducting current, the other is inactive. The instantaneous directions of current in the circuit for two successive halves of the cycle are shown in Fig. 94. With an arrangement of this kind the lower loop of the alternating-current wave of Fig.

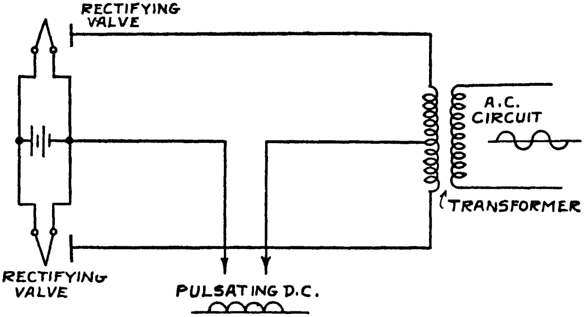

FIG. 93. A FULL WAVE RECTIFYING CIRCUIT UTILIZING TWO TUBES

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[2] U. S. Patent, 803,684.

92A is transposed above the zero line so as to give the pulsating current shown in Fig. 92C.

The development of the two-electrode tube was one of tremendous importance and it has led to other developments which are of far-reaching effect in the civilized world; but before we discuss these subsequent developments, it will be of interest to study further the principles involved in the mechanism of the vacuum tube.

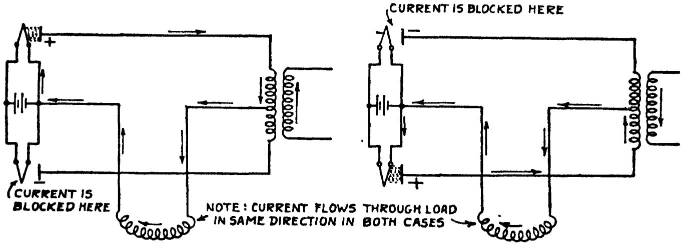
CURRENT IS BLOCKED HERE
+
−
CURRENT IS BLOCKED HERE
−
+
NOTE: CURRENT FLOWS THROUGH LOAD IN SAME DIRECTION IN BOTH CASES

FIG. 94. INSTANTANEOUS CURRENT DIRECTIONS FOR TWO SUCCESSIVE HALF WAVES OF AN ALTERNATING CURRENT

EFFECT OF PLATE POTENTIAL UPON ELECTRON EMISSION

In the preceding article, it was shown that the number of electrons emitted from the filament was a function of the filament temperature. Therefore, if the temperature of the filament is maintained constant, the number of electron emitted per sec. will likewise be constant.

It was shown also, that the number of electrons drawn to the positively charged plate was dependent upon the value of the positive charge. Thus with the filament temperature held at a constant value, as the potential on the plate is slowly increased from zero, the number of electrons drawn over to the plate also slowly increases. If the increase of plate potential is continued, however, a value of plate voltage will be reached, eventually, under which all of the electrons emitted from the hot metal, will be attracted to the plate. When this value is reached, any further increase of plate potential will cause no further increase in plate current. This is known as the saturation current. If the value of the plate current be plotted against plate potential, a curve will be obtained having the general shape shown in Fig. 95.

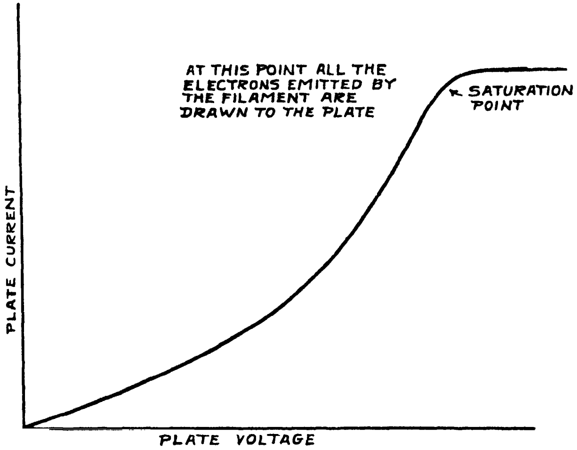

FIG. 95. VARIATION OF PLATE CURRENT WITH VARIATION IN PLATE VOLTAGE

Suppose, however, that we increase the temperature of the filament. Increasing the temperature increases the molecular agitation in the metal and results in an increase in the number of emitted electrons. Now, if we again increase the plate potential we will observe another increase in plate current, until a new saturation point is reached at which all of the emitted electrons are drawn over to the plate.

So, for each filament temperature, there is a definite saturation current which is obtained when the plate potential removes the electrons at the same rate at which they are evaporated from the filament.

HOW AN ELECTRON ESCAPES FROM A HOT METAL

It has been stated that the electrons escape from the solid metal of a hot filament by virtue of their kinetic energy. This implies that an electron must overcome a certain resistance or must do a certain amount of work in order to make its escape from the solid body.

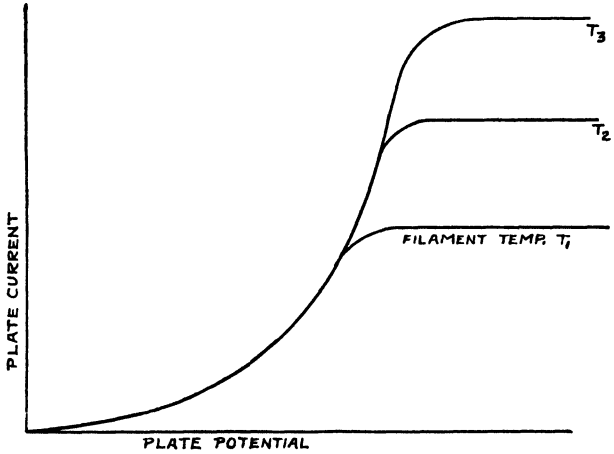

FIG. 96. SATURATION CURRENTS FOR VARIOUS FILAMENT TEMPERATURES

At low temperatures, the kinetic energy of the electrons is insufficient to enable them to break through the surface tension of the metal but as the temperature is raised the molecular agitation of the molecules is increased, causing an increase also in the agitation of the electrons.

Now it will be evident that, given a certain amount of kinetic energy, an electron very near the surface of the metal will have a better chance to escape than one farther away from the surface, since the latter will have to use up a certain proportion of its store of energy in first reaching the surface. An electron which has had to travel some distance say to reach the surface of the metal, may find upon reaching the surface that practically all of its store of energy has been spent so that if it does emerge it will be drawn back into the filament almost immediately. Another electron endowed originally with the same amount of energy, however, but located very near the surface will have a considerable store of energy left after breaking through the surface which will carry it a considerable distance away from the filament. It is for this reason that the distribution of electrons in the space surrounding a hot metal decreases in density as the distance from the hot surface is increased. Only those electrons having the highest velocities and located (at the start of their flight) comparatively close to the surface can reach any distance beyond the surface. Naturally, as the temperature is raised, the electrons travel to greater distances but at any time, regardless of the temperature, the electron density will always be very much greater near the surface of the metal than at some distance from it. In certain experiments by Morecroft,[3] he found that in a tungsten filament tube operating at normal operating temperature only 1/8000 of the electrons emitted reached a distance 0.15 cm. from the hot filament. Most of them perhaps never went farther than 0.001 cm. from the surface.

The amount of work which an electron must do to escape from a metal is perfectly definite for different metals and its value for any metal is called the "evaporation constant" of that metal. It is usually expressed in terms of the number of volts (the equivalent volts) through which an electron must drop in order to acquire sufficient kinetic energy to do this work.[4]

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[3] J. H. Morecroft. Principles of Radio Communication, p. 439.

The value of this factor, that is the number of volts through which an electron must fall in order to escape from the surface of a metal, is an exceedingly important one in the study of thermionics since it determines the amount of electron current that can be obtained from any particular type of cathode at any temperature. Its value varies for different substances, being considerably lower with elements such as thorium, lithium, and sodium, than for such metals as tungsten and platinum. For this reason, the filaments of modern vacuum tubes are often coated with barium oxide or are made of a mixture of tungsten and thorium. Such filaments provide a much larger electron emission at a certain temperature than would a plain tungsten or platinum filament at that same temperature. It is highly desirable to have cathodes with a low electron affinity as this property is called since the power that must be dissipated in the heating of the cathode to obtain a definite plate current decreases as the electron affinity decreases.

From this, it must be evident that the actual value of saturation current for a definite temperature of cathode and for a definite value of plate potential is dependent upon the character of the cathode. The actual saturation current I_s for a given filament temperature T in a tube having a perfect vacuum is given by the equation[5]

$$I_s = A\sqrt{T}\, e^{-\frac{b}{T}}$$

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[4] The evaporation constant and the equivalent volts are connected by the relation $\emptyset = \frac{w}{e}$ where $\emptyset$ = the equivalent volts, that is the number of volts through which the electron must drop, w = the evaporation constant and e = the charge on the electron (4.774×10^{-10} electrostatic units.)

in which I_s = the current of emission per sq. cm. of hot metal.
T = absolute temperature of the hot metal, C.
b = latent heat of evaporation of electrons = 105,000.
A = a constant, depending upon the physical structure of the elements.
e = the base of the natural system of logarithms, 2.718

EFFECT OF VARYING FILAMENT TEMPERATURE

Now, let us return to our study of the actual electron emission in the vacuum tube. Instead of varying the plate potential as was done in the above instance, let us vary the filament temperature while maintaining the plate potential constant at a particular value. When the filament is cold there can be no current flowing in the plate circuit since no electrons are being liberated from the filament. Suppose, now, that the filament is gradually heated. As soon as the temperature reaches a point where electrons are emitted, a current will begin to flow in the plate circuit which will increase as the temperature is raised higher. As the electrons are evaporated out of the filament they are drawn to the plate, and are absorbed by the latter. At any instant, therefore, there will be a certain number of electrons in

[5] This equation, it may be noted by those familiar with thermodynamic theory, is very similar to the equation which gives the number of atoms liberated during evaporation of a liquid. This is as follows:

$$N = A\sqrt{T}\, e^{-\frac{a}{2T}}$$

where N = number of atoms evaporating per second, per sq. cm. of surface.
T = Absolute temperature, C.
a = latent heat of evaporation.
A = a constant.
e = base of natural system of logarithms.

Thus it can be seen that the similarity between the evaporation of electron from hot metals and the evaporation of ordinary liquids extends even to the mathematical computations.

the space between the filament and the plate. As the temperature of the filament is still further increased, the electrons will be emitted at a rate faster than they can be absorbed by the plate, and as a consequence, the number of electrons in the space between the filament and the plate at a particular instant will be increased. In other words, the density of the electron cloud in the space will be increased.

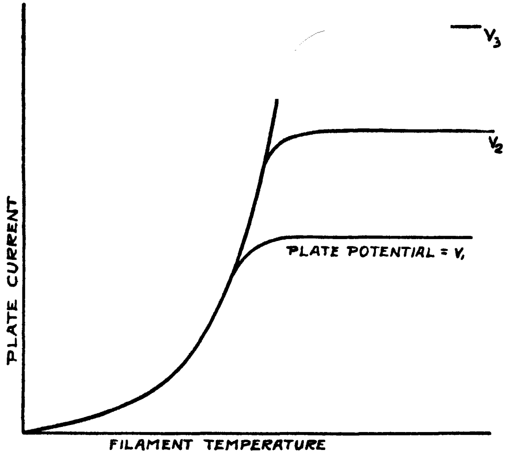

FIG. 97. PLATE CURRENT VARIATION WITH INCREASE OF FILAMENT CURRENT UNDER VARIOUS PLATE VOLTAGES

Being composed entirely of negative charges, this electron cloud as a whole will exert in the space between the filament and the plate an effect opposite to that of the plate. This is known as the space charge.

If the filament temperature is still further increased this space charge will gain in effect until, finally, a condition of equilibrium will be reached, the space charge overcoming the effect of the positive plate charge. When this condition is reached, the space charge will repel the emitted electrons, forcing them back to the filament. Beyond this point, no further increase in filament temperature will result in any further increase of plate current. If a greater plate current is desired, it will be necessary to increase the plate potential.

If the plate potential is increased, a further increase in filament temperature will again result in an increase of plate current until finally a new condition of equilibrium is reached. Thus, for every value of plate potential there is a corresponding value of filament temperature beyond which no further increase in plate current can be secured. The curves representing this effect are shown in Fig. 97.

Thus, it is seen that the operation of a tube of this kind say for the purpose of rectifying an alternating current, depends primarily upon two things, the plate potential and the filament temperature. There are other factors which, in practical devices, have a great effect on the operation but they may here be considered secondary factors. The amount of gas in the tube, for instance, has a distinct effect which in the practical application of the tube are of great value, but this, notwithstanding its importance, may be considered a secondary effect. The two things to be kept in mind are, the electrons are evaporated from the filament by virtue of its temperature, and they are attracted to the plate because of the value of the plate potential.

SPEED OF ELECTRON EMISSION

Before we close, it may be of interest to know something about the speed at which the electrons leave the surface of a hot metal. In the case of tungsten, it is known from certain experiments that an electron must fall through a potential difference of about 4 volts before it gains sufficient kinetic energy to overcome the restraining force at the surface of the metal.

Since we know the electric charge on the electron and its mass, it is a simple matter to determine the amount of kinetic energy gained during such a fall and from this, knowing the mass, the velocity at the end of its fall can be determined readily.[6]

Without attempting to follow through the calculations, it can be shown that if an electron falls through a difference of potential of one volt, it will attain a velocity of approximately 5×10^7 cm. per sec., that is about 311 miles per sec.

Since the surface tension with tungsten is such that a drop of 4 v. is necessary for an electron to break through, it can be shown that under these conditions an electron must have a velocity of 1×10^8 cm. per sec. or some 623 miles per sec. Of course, as has already been pointed out, if an electron approaches the surface of the metal from the inside at this speed, it will not break through, since part of its store of energy will be used in overcoming the resistance offered to its passage by the atoms and other electrons in the metal. If, under this velocity, they do manage to get through, their velocity upon emerging is spent and they at once fall back into the metal. So in order to attain any appreciable distance from the filament, the velocity of the electrons must be considerably greater than 623 miles per sec. Most of the electrons that manage to get through the surface (assuming that they are not in-

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[6] Since the potential energy lost is equal to the kinetic energy gained.

$$V e = \tfrac{1}{2} m v^2$$

in which V = the potential difference through which the electron has fallen in absolute electrostatic units; e = the charge on the electron (4.774×10^{-10}); m = the mass of the electron, and v = the final velocity of the electron.

From the above equation, by transposition we get

$$v^2 = 2 V \frac{e}{m}.$$

The value of $\frac{e}{m} = 5.3 \times 10^{17}$ electrostatic units.

fluenced by any extraneous field) do not travel far before falling back into the metal.

So it is seen that these tiny electrons travel with a great deal of speed—much faster than anything we are familiar with in ordinary matters. Here, in the vacuum tube, for the first time we can study their action apart from ordinary matter and it is because of this that the study of vacuum tube phenomena has shed so much light upon the fundamental theories of electricity and matter.

CHAPTER XXI

FURTHER CONSIDERATIONS REGARDING THE TWO ELECTRODE VACUUM TUBE

WHEN WE CONSIDER how very simple it is to evaporate electrons from a metal by heating it to a high temperature, it may seem surprising that the discovery of this phenomenon was delayed so long. The answer to this is, of course, that never until quite recently have we been able (even under this treating effect) to make the electron move fast enough in spaces sufficiently empty of air or other gases. We have shown that, merely to escape from a solid metal, an electron must attain a speed of some 600 mi. per sec. Even with

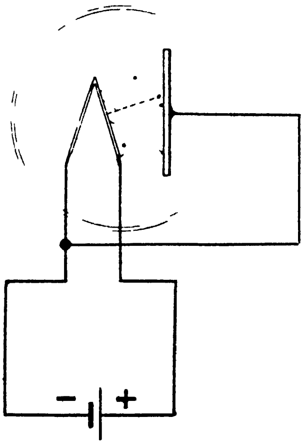

FIG 98 CIRCUIT ARRANGEMENT TO SHOW KINETIC ENERGY OF ELECTRONS DUE TO TEMPERATURE OF THE FILAMENT

In this case, since the plate is connected to the negative terminal of the filament, it is at the same potential as the filament, consequently there is no electrostatic field. Any electrons reaching the plate do so by virtue of their own kinetic energy.

10 times this speed it can move only a fraction of a millimeter through the air before losing its velocity and therefore, its power of going through the atoms. When Sir Wm. Crookes[1] first saw the cathode ray[2] stream its full course, it was because he had reduced the number of gas molecules in his bulb to such an extent that an electron could fly straight in a line from end to end of the bulb without going through more than perhaps a hundred atoms. Had there been air or other gas in the tube he never would have seen their effect, since their speed would have been destroyed in the first hundredth of an inch from the cathode.

So it was not until we were able to endow the electrons with high velocity and to free their path of nearly all atoms or molecules of gas that their effects became noticeable. It was under such conditions that Edison noticed their effect in imparting a charge to a plate within his lamp. While in Edison's lamp and in the rectifying tubes we have studied, the electrons are carried over to the plate by the positive potential imparted to the plate by an external electromotive force (the battery) it is possible, provided the vacuum is sufficiently high, for the electrons to fly to the plate under their own kinetic energy, that is, by the energy imparted to them by virtue of the temperature. To do this, they must have an exceedingly high initial velocity since it was shown that at normal operating temperature of a tungsten filament (2400 deg. C. abs.) only 1/8000 of the electrons emitted reach a distance of 0.15 cm. from the filament.

KINETIC ENERGY OF EMITTED ELECTRONS

John H. Morecroft of Columbia University, in experiments[3] along this line, found that a plate current existed in a tube even when the plate was at the same potential as the lowest potential point in the filament. A cold metal plate close to the filament was connected to the filament outside the tube as shown in Fig. 98; that is, the plate was connected to the *negative* terminal of the filament. Under these conditions, Edison, it will be remembered, found no current. This, however, was due to the fact that the plate in Edison's lamp was too far from the filament and the temperature of the filament probably was not high enough; the vacuum in his lamp,

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[1] Page 6

[2] Page 146.

[3] J. H. Morecroft, Principles of Radio Communication, p. 441.

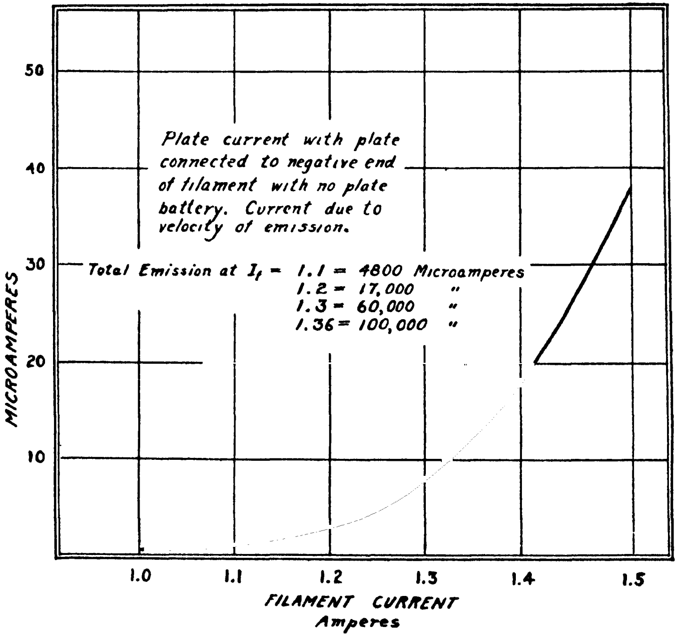

FIG. 99. ELECTRON CURRENT FROM A HOT TUNGSTEN FILAMENT TO AN ADJACENT COLD PLATE AT THE SAME POTENTIAL AS THE LOWEST POTENTIAL OF THE FILAMENT. CURRENT DUE ENTIRELY TO VELOCITY OF EMISSION OF ELECTRONS

also, probably was insufficient. In Morecroft's tube, the plate was 0.2 cm. from the plate and the vacuum was such as is obtainable today with improved exhausting equipment. The plate current observed was measured, of course, in micro-amperes (millionths of an ampere), and was due entirely to electrons emitted from the filament, with such a high velocity that their inertia actually carried them across the 0.2 cm. space separating the plate from the filament.

Figure 99 is a curve obtained by Morecroft, showing how the plate current due to this effect increased as the filament current and consequently the filament temperature, was increased. The total emission of electrons from the filament (that is, the number actually leaving the surface but *not necessarily reaching the plate*) expressed in terms of microamperes is given above the curve. With a filament current of 1.3 amp., the total emission is 60,000 microamperes. Since an ampere, we learned,[4] is a flow of over six billion billion (6.28×10^{18} or 6,280,000,000,000,000,000) electrons per second, a micro ampere is a flow of $6.28 \times 10^{18} \div 10^{6}$ or 6.28×10^{12} electrons per second. Therefore, with an emission current of 60,000 microamperes at 1.3 amp. filament current, the total number of electrons evaporated per second is $60{,}000 \times 6.28 \times 10^{12}$ or 3.768×10^{17}.

The plate current corresponding to this filament current (1.3 amp.) it will be noted from the curve is 7.2 microamperes, therefore, the number of electrons reaching the plate every second is $7.2 \times 6.28 \times 10^{12}$ or about 4.5×10^{13}.

Thus out of some 4000, million million electrons boiled out of the filament, about 45 million million or 1⅛ per cent are endowed with sufficient velocity to carry them across the 0.2 cm. separating the plate from the filament.

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[4] Page 182.

THE REAL SIGNIFICANCE OF THE ELECTRON'S "JUMP"

Now two tenths of a centimeter, according to our standards of measuring distance, is not much. It is, roughly, 0.08 of an inch and it would seem that no great expenditure of energy on the part of an electron would be necessary to enable it to jump that distance.

Suppose, however, that we look at this feat (of jumping two millimeters) from the point of view of the electron; in other words, let us compare this distance with the size of the electron to determine how many times its own length or diameter the electron must jump.

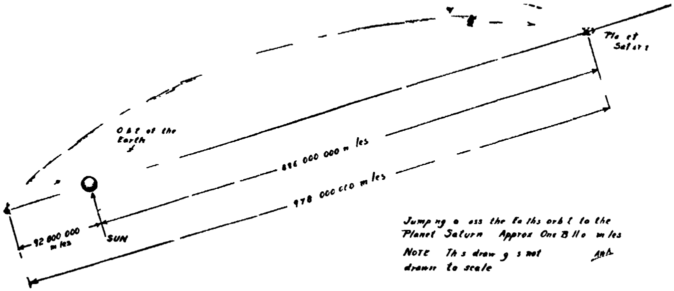
Planet Saturn
Orbit of the Earth
886 000 000 miles
978 000 000 miles
92 000 000 miles
SUN
Jumping across the Earths orbit to the Planet Saturn Approx One Billion miles
NOTE This drawing is not drawn to scale

FIG 100 IF A HUMAN BEING WERE TO JUMP THE SAME DISTANCE IN PROPORTION TO HIS SIZE AS THE ELECTRON DOES IN THE VACUUM TUBE, HE WOULD HAVE TO JUMP ONE BILLION MILES OR ROUGHLY TEN TIMES THE DISTANCE OF THE EARTH TO THE SUN

While it is rather meaningless to refer to the size of an electron since we do not know whether an electron has such a thing as size or not, from collision experiments it can be shown that the electron's active sphere of influence is roughly a five million millionth of a centimeter. To jump two tenths of a centimeter, therefore, an electron must cover 0.2 × 5,000,000,000,000 or one thousand billion times its own length, let us say.

To realize what this means, let us suppose that we as human beings were to jump the same distance in terms of our length. The average individual is just about 1/1000 of a mile long. Therefore, in jumping one million million times his own length, a human being would have to cover 1,000,000,000,000 × 0.001 or 1,000,000,000 miles or approximately ten times the distance which separates the earth from the sun!

An electron, therefore, in going from the filament to the plate in a vacuum tube undertakes a journey of considerable distance, and it is not to be wondered at that if any large number of obstacles beset its path, its chances of reaching its destination would be small indeed. For this reason, it is very essential that all air be exhausted from the tube.

In spite of our utmost efforts in this respect—even with the highest vacuum it is possible to produce with the most modern equipment, there will still be a tremendous number of gas molecules in the evacuated space. In the highest vacuums used today (10^{-8} mm. of mercury) there are still about one hundred million gas molecules per cubic centimeter. So, even with such vacuums, the electron must traverse hundreds of atoms to reach the plate. Apparently, since atoms can be traversed in this way, they must be very empty affairs.

EFFECT OF ELECTROSTATIC FIELD BETWEEN PLATE AND FILAMENT

So far, in this particular article, we have considered the electron making the journey to the plate entirely under its own kinetic energy. In the practical vacuum tube, however, as we have learned in the previous articles, the electron is impelled toward the plate as a consequence of the electrostatic field between the elements of the tube produced by an external source of positive potential. Under these conditions, its speed is very much greater than when moving under its own kinetic energy. With 100 v. positive potential on the plate, a velocity of some 6000 mi. per sec. is acquired while with 10,000 v., as is used in radio transmitting tubes and x-ray tubes, the speed acquired by the electron is over 30,000 mi. per sec.

Now, what becomes of the energy expended in accelerating the electrons in this manner? In our first illustration, that is, where the plate was connected to the negative lead of the filament, the electrons managed to reach the plate by virtue of the kinetic energy they gained in the thermal agitation of the molecules in the filament. In this latter case, however, an external source of potential is used to draw the electrons to the plate and since we know that when a charge moves under the influence of an electrostatic field, it does so at the expense of the energy stored in that field, the question arises, what becomes of that energy?

To answer this, we have merely to consider the further consequence of the electron's rapid flight to the plate. We know, from experience, that when a rapidly moving object is suddenly brought to rest, the kinetic energy of the object is usually converted into heat energy. When a bar of iron, for instance, is hammered upon vigorously, it (and also the hammer) will become heated. Similarly, where the course of a swiftly moving bullet is suddenly brought to rest by a steel plate, the temperature of the steel at the point of impact will be raised—the amount of heat produced being the equivalent of the kinetic energy of the bullet at the time of its impact.

In this same way, when a swiftly moving electron is suddenly stopped by a metal plate, the kinetic energy of the electron is transformed into heat. True, the mass of an electron is inconceivably minute but we have seen that at the moment it impinges against the plate it may be moving at velocities of anywhere between 1000 to 30,000 or more miles per second; its kinetic energy, therefore, despite its small mass, is considerable. The result then, of a stream of electrons impinging against the plate of an electron tube, is to raise the temperature of the plate. In vacuum tubes used for power purposes in radio, the electron bombardment is so great that in ordinary operation the plates are heated to a dull red heat. If the plate voltage on such tubes is raised to a sufficiently high value, the intense bombard-

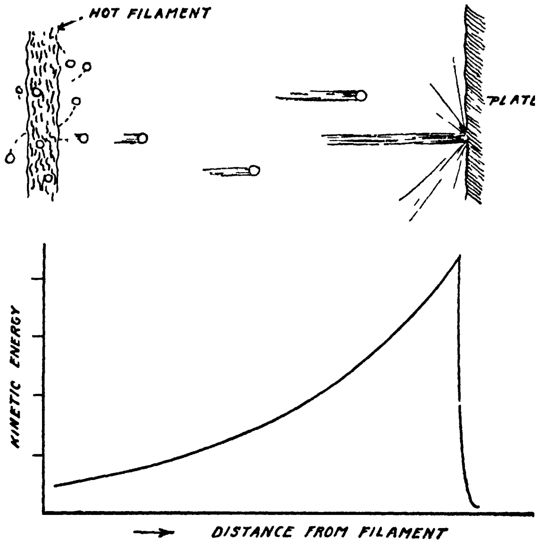

FIG 101. DIAGRAM AND CURVE SHOWING HOW VALUE OF THE KINETIC ENERGY OF AN ELECTRON VARIES IN ITS COURSE FROM THE FILAMENT TO THE PLATE

At the point where the electron leaves the filament, its store of kinetic energy is low. As it moves towards the plate, however, its store of kinetic energy gradually increases until, just as it collides with the plate, it is a maximum. Here, upon collision, the kinetic energy is converted into heat and as the electron enters the plate, its kinetic energy falls practically to zero.

ment will heat the plate to a white heat in a few seconds, resulting in the destruction of the elements.

HEATING OF PLATE EQUIVALENT TO HEATING OF SOLID CONDUCTORS BY PASSAGE OF CURRENT

This heating of the plate in an electron tube is equivalent to the heating effect due to resistance in a solid conductor. We have seen, in Chapter IX of this book that when an electric current is passed through a solid or liquid conductor, the movement of electrons among the molecules and atoms of the solid increases the molecular and atomic agitation, resulting in what we recognize as heat. In the vacuum tube, when we cause an electron to move to the plate we are supplying energy to it, but as long as its path remains clear and it meets with no obstacles, this energy will remain with it (the electron). Upon colliding with the plate, however, nearly all of this kinetic energy of the electron is converted into heat.

In the electron tube, therefore, there is thus a permanent expenditure of energy on the part of the plate battery similar in nature to that due to ohmic resistance of a metallic conductor. The energy supplied by the plate battery serves the useful purpose of attracting the electrons to the plate so that they may deliver their negative charges to it and thereby produce a current in the external plate circuit, but the energy from the battery which is represented by the motion of the electrons is permanently lost in heat at the plate as a result of the collision. It is evident, then, that the energy loss is directly proportional to the electromagnetic energy of the electron moving in the empty space of the tube.

From the above explanation, it is seen that the action of the electron in the vacuum tube is subject to the same laws that govern its action in solid and liquid conductors. In the solid conductor, the energy imparted to the electrons by the electrostatic field is given up with each of the numerous collisions with the atoms of the conductor. The distance through which a free electron in a conductor can move without colliding with an atom is comparatively short. In the vacuum tube, however, we have seen that an electron may travel hundreds of billions times its own diameter, without danger of colliding with many atoms, and for this reason all the energy supplied to it in the course of its travel from the hot cathode to the plate is retained until the instant the electron collides with the plate.

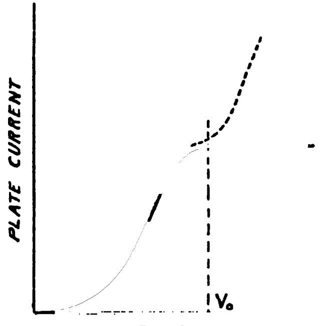

FIG. 102. CURVE SHOWING EFFECT OF IONIZATION OF GAS UPON THE PLATE CURRENT

Normally, with no gas present, the plate current curve is that shown by the full line curve, the saturation point being reached at the potential Vo. With gas in the tube, however, when the potential Vo is attained, ionization starts resulting in the increase of plate current shown by the dotted line curve.

EFFECT OF GAS IN A VACUUM TUBE

Thus far, in our consideration of the action of the electron in a vacuum tube, we have assumed that the space between the hot filament and the plate is free of all atoms of gas or air; in other words, we have assumed a perfect vacuum.

This, however, is a condition quite unattainable, for no matter how well we exhaust a tube even with the most modern equipment, there will still be a large number of gas molecules or atoms in the tube. The effect of these few remaining molecules in the ordinary action of the tube is quite negligible.

Suppose, however, that there is a larger amount of gas in the tube. What will be the consequences? The early types of vacuum tubes were not well evacuated and there was often a considerable amount of gas (compared to modern practice) left in them which made their behavior erratic. Not only would various tubes, supposedly similar, have widely different characteristics but the same tube would act differently at different times. The reason for this was found to lie in the presence of the gas within the tube.

In the high vacuum tube, so far considered, the only current passing between the filament and the plate was due to electrons which were actually evaporated out of the filament. The space between the filament and the plate was not a conductor and the electron current was in no way dependent upon the nature of this space as long as it was devoid of atoms and molecules.

Suppose, however, that we introduce some gas into this space. Ordinarily, gas is a good insulator and will not carry current but when under rather low pressures it may be made to carry large currents, if by some means it becomes ionized. This, it may be recalled, was explained in Chapter VI of this series, in connection with the theory of conduction through gases.

By ionization, we mean the breaking up of a gas atom into two parts, a free electron, and a positively charged ion (that is the normal atom with an electron removed). This, as explained in Chapter VI, is often the result of a collision between a high speed electron and an atom.

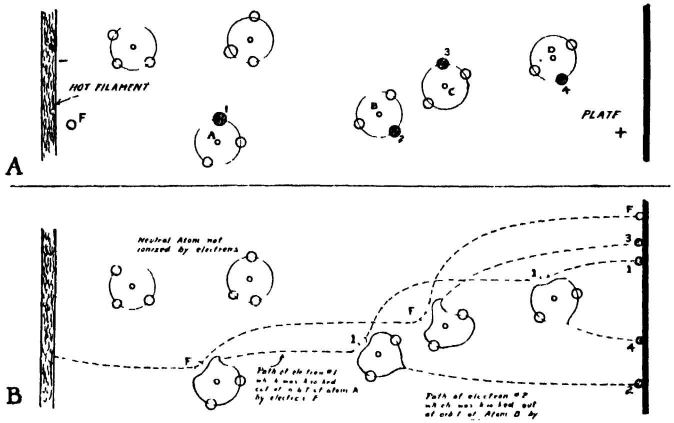
A
HOT FILAMENT
F
A
1
B
2
3
C
D
4
PLATE
+
B
Neutral Atom not ionized by electrons
F
1
Path of electron #1 which was knocked out of orbit of atom A by electron F
F
1
Path of electron #2 which was knocked out of orbit of Atom B by
F
3
1
4
2

FIG. 103. DIAGRAM TO SHOW HOW IONIZATION BY COLLISION INCREASES THE VALUE OF THE PLATE CURRENT

At A is depicted crudely the position of a number of normal atoms of gas between the filament and the plate of a vacuum tube, each atom having one of its electrons designated by a number, 1, 2, 3, etc. At B is shown the condition after the electron F has collided with some of these atoms, the dotted lines showing the paths of the different electrons after they had been knocked out of the atoms. Instead of only one electron reaching the plate as would have been the case had no gas been present, five electrons are shown reaching the plate—the original electron emitted by the filament, and the four knocked out of the atoms.

Now it is evident that if there are gas molecules or atoms in the path of the electrons journeying between the filament of a vacuum tube and the plate, there will be numerous collisions between the atoms and electrons, and if the velocity of the latter is sufficiently high the impact of collision will disrupt the atoms. This splits the atoms up into free electrons and positively charged ions, which travel, respectively, toward the plate and the filament producing an increase in the plate current.

This action is shown in Fig. 102 where the dotted line curve shows an increase in plate current after the ionization voltage V_0 is reached. Normally, without any gas in the tube, the plate current would not increase after the potential V_0 was attained, but with gas in the tube, when V_0 is reached, the velocity of the electrons is high enough to cause ionization of the gas atoms.

Since the electrons leaving the filament are gradually accelerated as they near the plate, they attain their maximum velocity upon reaching the plate, naturally we would expect ionization to begin in the immediate vicinity of the plate and this is actually the case. As the voltage on the plate of a vacuum tube containing gas is increased, a blue glow will first appear around the plate. This blue glow is the direct result of ionization. It is the result of recombination of certain of the ionized atoms; that is, after an atom has been ionized, it may, before travelling very far, recombine with another free electron, forming once again a neutral atom. This phenomenon will be treated in detail in a subsequent article.

The ionization effect in vacuum tubes is cumulative. Suppose an electron is knocked loose from an atom by collision with a high velocity electron travelling toward the plate. The newly freed electron will at once be acted upon by the field or will be accelerated toward the plate. As it gains velocity, this electron in turn will ionize another atom and so on. Thus, in a short interval of time, there will be a very large number of free electrons in the tube, causing a large increase in current.

This process of ionization, while detrimental to the operation of vacuum tubes used in radio work, is used to excellent advantage in the case of rectifying tubes such as have already been referred to. In the Tungar rectifier, the tube is filled with an inert gas (usually Argon, at about 2 lb. absolute pressure) and this gas is ionized by the electrons, emitted by the hot filament. The carrier of the plate current is in this case mostly ionized gas, the number of electrons emitted from the filament being sufficient to carry perhaps 1/500 of the current to the plate. Tubes of this type are used only in low voltage work. Where high potentials are to be rectified, the tubes are usually made with as high a vacuum as it is possible to obtain and the plate current is never higher than that actually emitted by the filament.

Before we conclude this discussion of the effect of gas upon electron currents, it may be well to explain briefly, what becomes of the positive ions, produced by the collision between electrons and neutral atoms. As already mentioned, these are drawn toward the hot filament, due to the fact that it carries a negative charge; but since these positive ions are many thousands of times large than the electrons, their progress is proportionally slower. Nevertheless, if the potential gradient is high enough, these positive ions will also gain sufficient velocity to ionize other neutral atoms, resulting in still another increase in current.

So it is evident that the effect of gas in a vacuum tube is quite important not only because of its beneficial or detrimental effect in actual tubes, but because of the insight which a study of the phenomenon affords us in understanding the role of the electron in other processes.

CHAPTER XXII

THE THREE ELECTRODE VACUUM TUBE

WE NOW COME TO AN application of the thermionic principle, which is of great significance not only because it forms the basis of the modern radio industry and has made possible transcontinental telephony but because it has given us a more thorough understanding of electrons and their behavior than would have been possible without it. The application we have reference to is that made in the "three-electrode" vacuum tube.

The vacuum tubes we have thus far considered have had only two electrodes, one a negative electrode consisting of a hot filament and the other, a positive electrode consisting of a cold metal plate. This type of tube, we learned, can be used to rectify alternating current. The three-electrode tube which we are now to consider, differs from the two-electrode tube in that a third electrode, called a grid, is interposed between the filament and the plate for the purpose of controlling the plate current. The grid usually takes the form of a fine wire mesh or screen; the electrons passing from the filament to the plate must pass through the holes in the mesh and their passage to the plate is controlled to any desired extent by varying the potential of this grid. The usual arrangement is that shown in Fig. 104. It so happens that while the plate current may be of considerable magnitude and the amount of power quite high, the amount of energy necessary to effect its control by means of the grid may be extremely small.

In the previous articles, we have shown that the strength of the plate current (for a given filament temperature) is dependent upon the intensity of the electrostatic field set up by the potential difference between the filament and the plate. We also learned, in our study of the electric field,[1] that the force between two electric charges varies inversely as the square of the distance between them. In a given vacuum tube, therefore, for a certain plate potential it would be possible to increase the plate current by decreasing the distance between the filament and the plate.

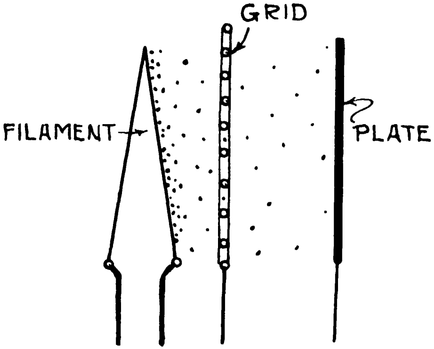

FIG. 104. THE ELEMENTS OF A THREE ELECTRODE VACUUM TUBE

Suppose that, instead of moving the plate closer to the filament, we place a grid in between the filament and the plate as shown in Fig. 104 and impart a slight positive charge to this grid by connecting it to the positive terminal of a battery. It is evident that this positively charged grid will aid the plate in drawing electrons to it. Since the grid is much closer to the filament, a much smaller positive charge is necessary to exert a given attraction than would be necessary by applying the charge to the plate. If, instead of charging the grid positively, it is given a negative charge, the electrons emitted by the filament will be repelled by the negative charge on the grid and a smaller proportion of them will reach the plate. If the negative charge is increased, the effect of the positive charge on the plate may be neutralized entirely, reducing the plate current to zero.

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[1] Page 56.

TUBE FUNCTIONS AS A RELAY

This is a simple explanation of the function of the grid in the three-electrode vacuum tube. The tube in fact is a relay. In Fig. 105 is shown a simple relay. When the magnet M is energized by weak current from the battery B, due to the key K being closed, the armature A is attracted downward. This closes a pair of contacts C one of which is carried by the moving armature A, thus permitting current from the local battery L to flow in the bell circuit. In this way a large bell requiring comparatively heavy current, can be operated from a distant source by a current too weak to operate the bell direct. In this analogy, the magnet M corresponds to the grid in the three-electrode vacuum tube. The vacuum tube is a much more sensitive relay than any mechanical relay ever constructed, for the simple reason that the moving parts (the electron stream) have no inertia.

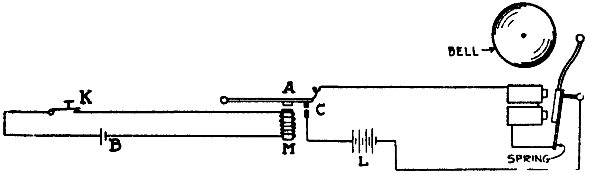

FIG. 105. A SIMPLE RELAY OPERATING AN ELECTRIC BELL

To understand fully the factors that control the action of the three-electrode vacuum tube, it is necessary to investigate its action more in detail.

MORE CONCERNING THE SPACE CHARGE

In one of the previous chapters,[2] brief mention was made of the so-called "space charge." This, it may be recalled, was the negative influence of a cloud of electrons in the immediate vicinity of the hot cathode. The three-electrode vacuum tube functions because of the effect of the grid on the space charge in the tube or to express it in another way, because of its effect on the potential distribution between the filament and the plate.

In previously considering the action of the vacuum tube, it was assumed, or rather nothing was said about it, that the potential gradient between the filament and the plate is uniform. Actually, this is not true. The gradient is less near the filament, for two reasons: first, because of the comparatively small surface of the filament with respect to the plate, and second because of the electron cloud surrounding the filament.

In Fig. 106 is shown a diagram illustrating crudely, the relative distribution of electrons between the hot filament F and a plate P carrying a positive charge. As already explained, the density of electrons is considerably greater near the filament than it is near the plate, due to low velocity electrons falling back into the filament. Now let us consider the forces acting on two electrons, one at A, close to the filament and another, B, near the plate. The one at B is urged toward the plate by two forces: first, the attraction of the plate and second, the repulsive effect of all the electrons between it and the filament. The electron at A is also acted upon by two forces, first the attraction of the plate and second the repulsive effect of all the electrons between it and the plate. In this case, however, the repulsive effect of the electrons is opposite to the attractive effect of the plate and whether the electron at A will move toward the plate or the filament will depend upon which of the two forces is stronger. Very close to the filament, the combined repulsive effect of all the electrons between the filament and the plate will practically neutralize the attractive effect of the plate unless the plate voltage is high enough to give an attraction greater than the repulsive effect exerted by the space charge. From this it is evident that the potential distribution in a vacuum tube is not uniform but is less near the filament than it is near the plate.

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[2] Page 207.

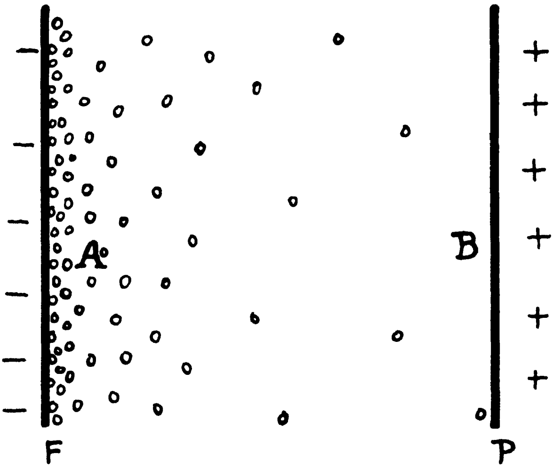

FIG. 106. DIAGRAM SHOWING THE DISTRIBUTION OF ELECTRONS BETWEEN THE FILAMENT AND PLATE OF A VACUUM TUBE

An electron at B is not only urged to the plate by the attraction of the positive charge but is also by the repulsion of all the electrons in the space between it and the filament. An electron at B, however, although it may be attracted by the plate, is repelled in the opposite direction by all the electrons between it and the plate.

To make this more clear, consider the potential gradient between two cold metal plates, shown by the straight sloping line a in Fig. 107.[3] Here the potential gradient is uniform as would be expected.

Suppose, however, that electron atmosphere is made to surround the negative plate by heating it to a high temperature. Many of the lines of electrostatic force formerly (when no electron cloud existed) extending from the positive plate to the negative plate, will now terminate on electrons near the negative plate. Thus, many of the lines leaving the positive plate never reach the negative plate. This is shown in Fig. 108. Under these conditions, the potential distribution curve instead of being a straight line as shown in Fig. 107, a, takes the form shown in b. If the electron emission is

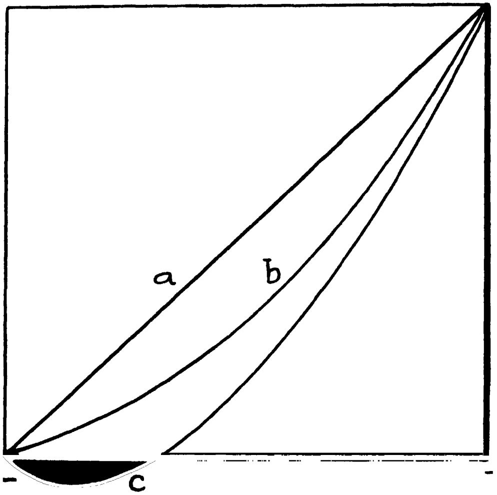

FIG. 107. DISTRIBUTION OF POTENTIAL BETWEEN TWO PLATES UNDER VARIOUS CONDITIONS

a represents the potential gradient between two cold metal plates. b is the potential gradient curve when the negative plate is surrounded by electrons. c represents the potential gradient when the electron emission is considerably greater than the plate current.

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[3] J. H. Morecroft, Principles of Radio Communication, p. 458.

much greater than the plate current as is usually the case in ordinary vacuum tube operation, the potential very close to the surface may even become negative, resulting in the curve shown in Fig. 107c.

Now, by placing a grid between the plates and charging this grid positively or negatively, the shape of the curve b can be changed. This is shown in Fig. 109. If the grid is not given any charge, it will exert no effect and the curve representing the voltage gradient will be as at a.

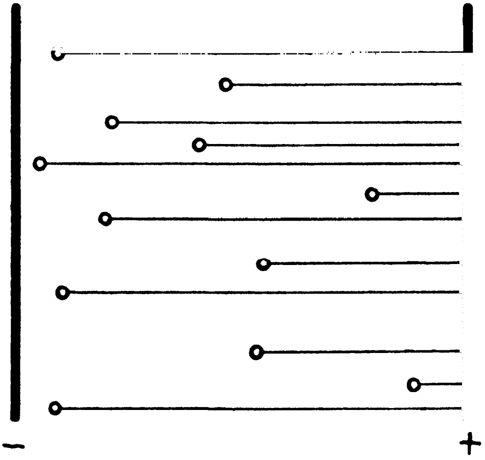

FIG. 108. DIAGRAM SHOWING WHY THE POTENTIAL GRADIENT IS LOWER NEAR THE FILAMENT THAN IT IS NEAR THE PLATE

Lines of force extending from the positive plate, terminate on electrons in space instead of on the filament. There are thus more lines of force entering the positive plate than the filament.

If the grid is made positive, however, the potential gradient in the space between the negative plate and the grid, is greatly increased. Many low velocity electrons which, without this increase of potential, would have fallen back into the negative plate without the additional field set up by the grid are now drawn away toward the grid. What really has occurred is that the space charge has been neutralized to a considerable extent.

The electrons which are thus drawn to the grid are now acted upon by the combined attractive force of both the grid and the plate. As an electron approaches the grid, it has two alternatives: it may attach itself to the grid, thereby neutralizing one of the positive charges on the grid, or it may pass through one of the holes in the grid and continue on to the plate. A comparatively small number of electrons do attach themselves to the grid but the majority pass through the openings and go to the plate.

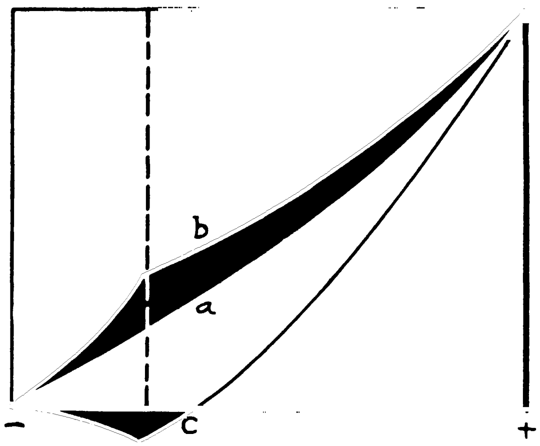

FIG. 109. SHOWING THE EFFECT OF THE GRID ON THE POTENTIAL DISTRIBUTION IN A TUBE

a is the potential gradient curve with the grid uncharged. b shows the gradient with a positive charge on the grid and c with a negative charge on the grid.

An electron moving toward the grid may find itself in either of two positions: it may be traveling on a line which passes directly through one of the wires constituting the grid, as at A, Fig. 110, or it may be moving along a line passing between the grid wires, as at B, Fig. 110. If it happens to be the former, the chances are that the electron will go to the grid since there are no forces acting to make it deviate from its straight course. In position B, however, the electron will certainly continue towards the plate, because of the higher potential and greater surface of the plate. Thus, the introduction of a positively charged grid between the filament and the plate will cause more electrons to reach the plate than would be the case without it. The positive grid has the effect of reducing the space charge and changing the shape of the potential distribution curve to that shown in Fig. 109b.

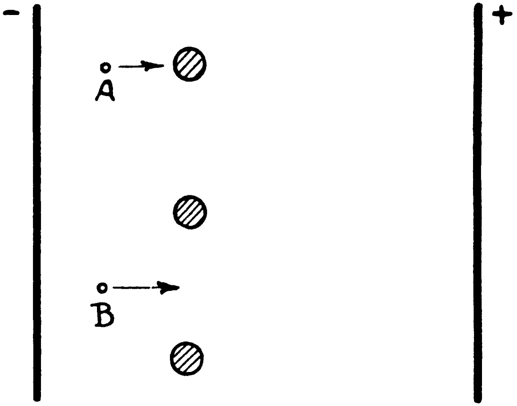

FIG. 110. POSSIBLE POSITIONS OF ELECTRONS IN A THREE ELECTRODE TUBE

The electron at A is almost certain to pass into the grid. The electron at B, although attracted by the grid will continue on to the plate.

If the grid is given a negative charge, however, electrons emitted by the filament will be repelled by the negative charge on the grid and practically none of them will reach the plate. Under these conditions, the potential distribution curve will assume the character of C in Fig. 109. The point to be kept in mind in visualizing the action of the three-electrode vacuum tube is that the grid potential necessary to control a large plate current is small.

From the above explanation, it will be evident that any variation in the potential of the grid, will effect a corresponding variation in the plate current. If the grid potential is increased (positively) the plate current will increase; if it is reduced, the plate current will be reduced. If the grid is made negative, the plate current will decrease still more and at a certain negative grid potential the plate current will fall to zero.

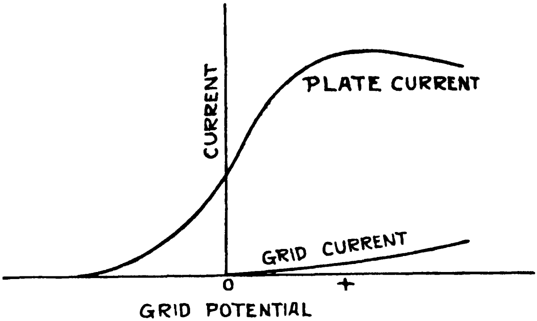

FIG. 111. CURVE SHOWING VARIATION OF PLATE CURRENT WITH GRID POTENTIAL

Figure 111 shows the variation in plate current with grid potential, for a given plate potential. As may be noted, as the grid potential is varied from negative through zero to positive, the plate current gradually increases until the saturation current[4] corresponding to the filament temperature is reached. As the grid is made increasingly positive, a greater number of electrons will be attracted to the grid, resulting in a slight *grid current* with a corresponding slight drop in plate current. It is evident that the production of a grid current is done at the expense of the plate current.

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[4] Page 202.

HOW A THREE-ELECTRODE TUBE AMPLIFIES

Suppose, now, that instead of merely applying a positive or negative potential to the grid, an alternating potential is applied; what will be the result? In Fig. 112, an attempt is made to show this. A definite steady negative voltage is first applied to the grid by means of

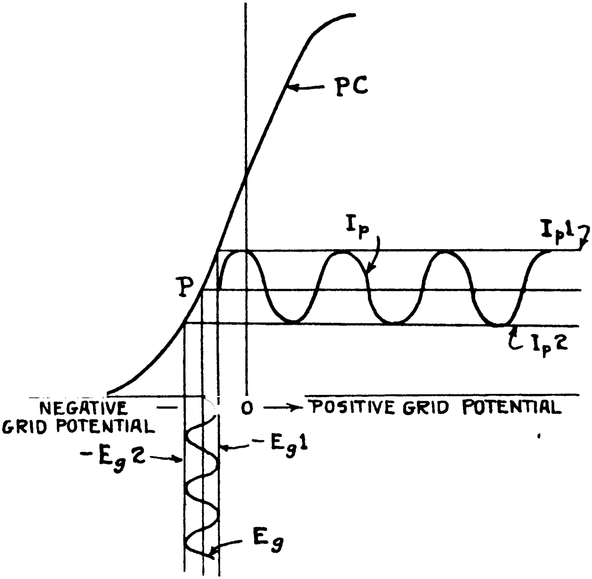

FIG. 112. DIAGRAM SHOWING THE AMPLIFICATION CHARACTERISTICS OF THE THREE ELECTRODE VACUUM TUBE

Eg is the alternating potential impressed on the grid. Ip is the alternating current produced in the plate circuit.

a small battery, C, in Fig. 113. This gives a definite operating point P on the plate current-grid voltage curve, Fig. 112. A small alternating voltage Eg is superimposed on this steady voltage by connecting a source of alternating voltage, as shown in the circuit diagram, in the grid circuit. With such an arrangement the grid voltage will vary as shown between Eg1 and Eg2. Since each variation in grid potential produces a corresponding variation in the plate current, the wave e_g may be projected vertically to the curve PC and then horizontally producing the wave Ip. Thus, the introduction of an alternating potential in the grid circuit results in the production of an alternating current in the plate circuit which is superimposed on the steady plate circuit due to the battery B in Fig. 113. This alternating current may be considered as being produced by a voltage f_a e_g acting through a constant plate resistance rp. In this expression, the term f_a is called the amplifying factor of the tube. It will be noted that the alternating current in the plate circuit varies between much wider limits than does the alternating voltage in the grid circuit. This, of course, is due to the steepness of the slope of the curve PC.

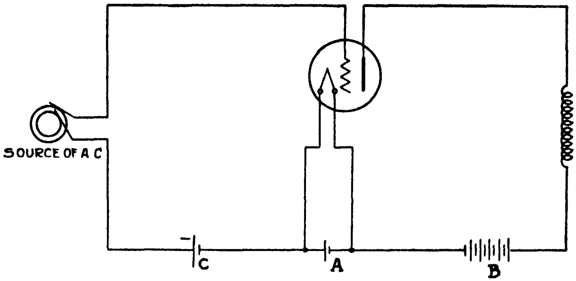

FIG. 113. CIRCUIT USED TO PRODUCE CONDITIONS SHOWN IN FIG. 112

A three-electrode vacuum tube, therefore, may be made to function as an amplifier of alternating current and in this capacity it has received great application in the radio field. From the diagram shown in Fig. 112, it will be evident that the voltages Eg1 and Eg2 should be selected so as to compel the alternating current to operate on the straight part of the characteristic curve. If the point P, for instance, had been moved down lower on the curve, the resultant alternating current in the plate circuit would no longer be symmetrical and a distorted wave would be produced. The point P can be moved anywhere along the length of the curve PC by merely impressing the proper grid voltage on it. This, in radio circuits, is usually done by means of what has come to be known commonly as a "C" battery. The more technical designation is the grid bias battery.

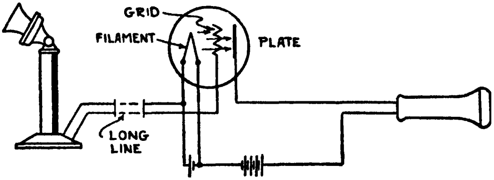

FIG. 114. SHOWING THE PRINCIPLE OF THE TELEPHONE AMPLIFIER

In modern three-electrode tubes, the amount of power taken by the grid is so small that the power in the plate circuit which it controls may be thousands of times as great. Certain tubes used as amplifying repeaters have power amplifications of about one thousand times.

THE TELEPHONE REPEATER

This particular application of the three-electrode tube is of considerable interest. In an ordinary telephone line, the voice current falls off in intensity very rapidly as the length of the line increases. For local communication, this is not a serious matter but for long distance telephoning it is a limiting feature. To overcome, or rather to counteract this effect today, amplifying repeaters are placed in long distance lines at definite intervals. In Fig. 115 is a diagram showing how the value of the voice current decreases in intensity and how it is amplified by vacuum tube repeaters along the transcontinental telephone line. In this way, the intensity of the voice current can be controlled to any desired extent, the received current at New York often

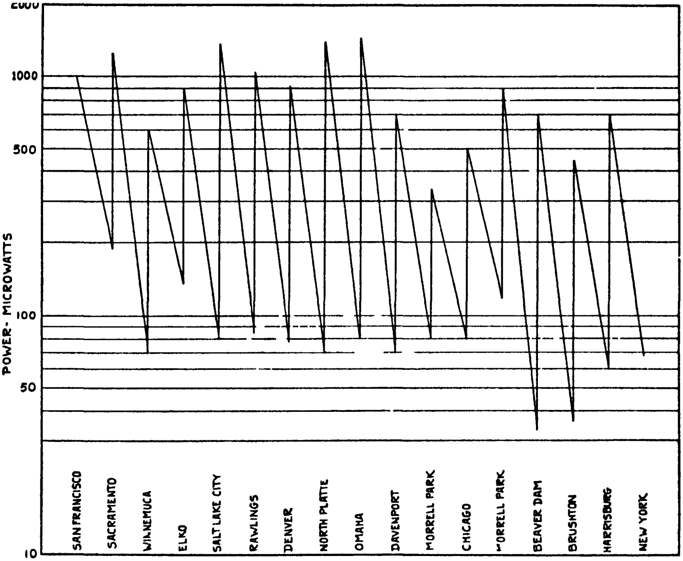

FIG. 115 POWER LEVELS OF SAN FRANCISCO-NEW YORK TELEPHONE LINE, SHOWING EFFECT OF REPEATERS

With 1000 microwatts input at San Francisco, the power drops to slightly under 200 mw. at Sacramento. Here the current is amplified by vacuum tube repeaters to a value of over 1000 mw. This new high level falls to 70 mw. by the time it reaches Winnemuca where it is again amplified. Thus, the voice current is amplified successively 15 times before it reaches New York City.

being higher than it was when it left San Francisco. At each repeater station, the gain in intensity is effected by an addition of power supplied from local batteries. The principle is the same as that illustrated in Fig. 105 where a weak current is made to ring a powerful bell through the relay. The three-electrode vacuum tube is an amplifying relay.

It is of interest to know that, without the repeater, transcontinental telephony would be virtually impossible. For instance, on the San Francisco-Havana line, with the transmitter delivering 1000 microwatts at San Francisco, the power delivered at Havana at the end of the 5500-mi. circuit is about 25 microwatts. If there were no intermediate amplifiers and assuming that the line could carry unlimited power without burning up, it would be necessary, in order to deliver 25 microwatts at Havana, that power sufficient to light an ordinary incandescent lamp would be flowing in the circuit at some point in North Carolina while at Philadelphia the power would be 5 kw. A little east of Denver the line would be carrying the equivalent of all the electrical and mechanical power generated in the world (enough to light 20 billion electric lamps). This is about 1/200,000 of the power which is received by the earth from the sun. Yet at Sacramento all of this power (200,000 times all the power generated on earth) would have to be flowing in the line to produce 25 microwatts at Havana.[5]

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[5] H. S. Osborne, Telephone Transmission Over Long Lines. Proceedings of the A. I. E. E., Vol. XLII, p. 984.

CHAPTER XXIII

THE DISRUPTIVE DISCHARGE

IF WE WERE TO CONTINUE our discussion of the three-electrode vacuum tube, we should be led, inevitably, into a detailed consideration of "radio" for it is in the radio field that the vacuum tube has received its greatest application. This, however, would take us ahead of our story. Radio is a wave phenomenon involving a familiarity with the principles of electromagnetic radiation and as these have not yet received treatment, it will be necessary to defer further consideration of the vacuum tube and its applications until certain other preliminary matters have been touched upon.

We still have more to learn about ionization. The reader who has thus far had the patience to follow this book may wonder occasionally why so much stress is given to the process of ionization—is it of such great importance?

Without ionization, we should know practically nothing of electricity, for ionization, as we have seen is the process whereby neutral atoms are broken up into positive and negative electrical components. Since it is the behavior of these components in attempting to establish neutralization that is responsible for all electrical phenomena, it will be evident that ionization is of exceedingly great importance.

Ionization, we have seen, plays an important role in the process of gaseous conduction and we have studied its action in quite some detail in the vacuum tube. Outside of the vacuum tube, perhaps the most interesting result of ionization in gases is the electric arc. The electric arc is of major importance in electrical engineering and was without doubt the first electrical phenomenon to be observed by man, for natural lightning is one form of the electric arc. While the electric arc has many useful applications, it also has destructive characteristics which have caused electrical engineers a great deal of worry.

ARC PHENOMENA ARE COMPLEX

Despite the seeming simplicity of an electric arc, it is very complex in nature and its behavior is often erratic. It is difficult to carry on consistent experiments with the arc. As Dr. Slepian[1] of the Westinghouse Company aptly puts it, "A very profound characteristic of the arc is its strong 'won't.' When the engineer tries to make a good automatic welding machine or a good arc lamp, he naturally wants the arc to burn smoothly and strongly but he is troubled because the arc wants to flicker and fuss and go out. On the other hand, when he tries to build a switch. then an arc forms at the contacts which burns steadfast and true."

An arc may be defined as a discharge of considerable current at comparatively low voltage in a gas or in air between electrodes. An ordinary gas, at atmospheric pressure and temperature, is a good insulator, being made up almost entirely of neutral atoms. These normal atoms, we know consist of equal positive and negative electrical charges, and exhibit no electrical effects of any kind. They may be considered as perfectly married couples, not given to "cutting loose." Among these neutral atoms, however, there are always present a number of free ions moving about at various velocities. These free ions do not possess the virtue of consistency as do those which make up the normal atoms. They have entered into a sort of companionate marriage arrangement in preference to the more orthodox arrangement of the normal atom. These move about, now staying awhile with one atomic system, then moving on to another. Occasionally two of them of opposite charges meet and form a neutral atom. Often, however, a fast moving negative ion or electron will collide with a neutral atom with such force as to disrupt it. Such disruptions normally are balanced by the number of recombinations so the total number of free ions in a gas remains constant.

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[1] Theory of the Electric Arc. Journal, Western Soc. of Eng., April, 1928.

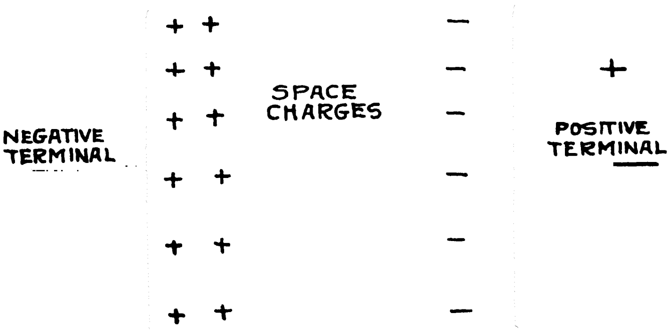

FIG. 116. SHOWING THE SPACE CHARGES NEAR THE TERMINALS OF AN IONIZED GAS SPACE

EFFECT OF ELECTRIC FIELD

When a voltage is applied across a gas, as in the case of an ordinary spark gap, the mean velocity of the free ions rises and more new ions are produced by collision but as long as the voltage remains moderate, only a minute current will flow. These newly formed ions, if the gradient continues to be maintained, may also generate more ions by collision. Thus, starting out with only a few charged particles in a gap, by the application of sufficiently high voltage great conductivity may be developed, and the current may rise to a large value. When this occurs, we have what is known as a luminous or disruptive discharge. This is the type of discharge that occurs when a solid insulator breaks down as described in Chapter X.[2] It is not quite clear at the present time whether the breakdown of a solid insulator is due to the pressure of gaseous ions in the solid material or to an actual breaking down under the electrostatic stress of the neutral atoms.

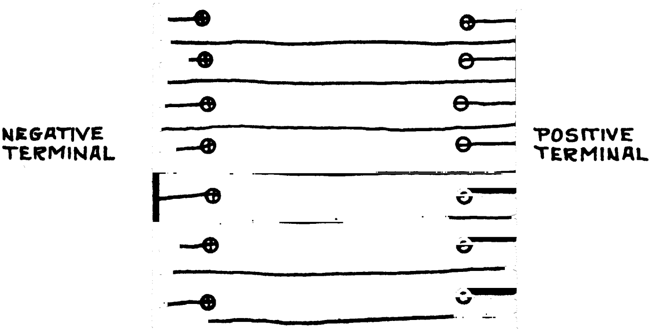

FIG 117. DIAGRAM SHOWING HOW THE LINES OF FORCE EMANATING FROM THE TERMINALS, TERMINATE ON THE SPACE CHARGES

Thus, the formation of an electric arc or spark by merely impressing a high potential across a pair of electrodes is caused by ionization by collision. The entire phenomenon, therefore, hinges upon the fact that all gases at ordinary temperature and pressure contain a small number of free ions. If there were no free ions in the gas to begin with, there would be none to accelerate by means of the field and no matter how long the voltage was maintained, no current could flow. Of course, it is conceivable that if the voltage were raised sufficiently high, the neutral atoms themselves would be strained to a rupturing point and thus ions would be produced. The voltage necessary to rupture a neutral atom in this manner is greatly in excess of that ordinarily required to cause a discharge in a gas, so in the consideration of arc phenomenon, this action need receive no consideration.

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[2] Page 96.

PROOF THAT THE ARC IS DUE TO PRESENCE OF IONS

That the formation of an arc by the breaking down of the insulating qualities of a gas is due to ions existing initially in the gas can be demonstrated effectively by shielding the gas from all possible sources of ionization.

The ions existing initially in ordinary gases are produced by a number of agencies. Research has shown that gases can be ionized by means of x-rays or ultra-violet light or by the rays of radium. When a beam of x-rays is passed through a gas consisting of neutral atoms, some of the atoms will be ionized. The reason for this will be discussed in subsequent articles in the consideration of radiation. Similarly, ultra-violet light will cause ionization and the rays from radium are very potent in this respect.

In the atmosphere surrounding the earth, all of these three types of radiation are present to a certain extent. The radiation coming from the sun is composed not only of visible light, but also ultra-violet and other short wave radiation. Recently Millikan has shown, by experiments in the high Andes, that other penetrating radiation is coming to us from all points of space. With all these rays acting on the atmosphere, it is natural that the gases of the atmosphere should be ionized. Since the earth contains comparatively large quantities of radium and other radio-active material, rays capable of ionizing gases are also issuing from the earth. From this, it will be apparent that it would be difficult to isolate a gas so that none of these ionizing agencies could act on it.

It has been shown, however, that by merely enclosing a spark gap in a dark chamber, thus shielding it from the effect of ultra violet rays, the initial ionization can be reduced to so small a value, that the time for ionization to build up may become quite large. Townsend,[3] in investigating this, found that when a gap was enclosed in a dark chamber for some time before applying a voltage, a voltage in excess of the normal breakdown voltage could be applied for several seconds before breakdown occurred.

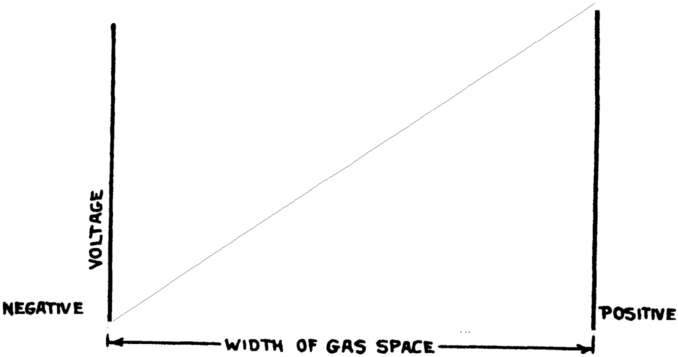

FIG. 118. POTENTIAL GRADIENT ACROSS A NON-IONIZED GAS SPACE

THE DISRUPTIVE DISCHARGE

Thus far, although it was our intention to study the electric arc, we have in reality considered only the disruptive discharge which must occur before a true arc can form. A true arc is a discharge characterized by a low resistance as compared to that of the disruptive discharge. Of course, an arc can be formed in another manner without being preceded by the disruptive discharge, that is, when a circuit carrying current is opened by separating a pair of contacts, but this method of forming an arc will be considered later.

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[3] Conduction in gases.

The disruptive discharge may take a variety of forms. It may occur in the form of a spark, or as a uniform glow or as a brush discharge, the form depending upon the form of the electrodes and the pressure of the gas. At ordinary pressures if the electrostatic field is uniform between the electrodes, conduction will take place in the form of a spark. If the field is relatively intense near an electrode, however, the gas in that region is disrupted, before that in other portions of the space between electrodes, resulting in a local glow which is known as the corona.

The disruptive condition is due mainly to ionization throughout the gas, the electrodes having only a secondary effect. The gas molecules have two effects: first they furnish the ions which carry the current; and secondly, they impede the motion of these ions. At low pressures, or with small distances between electrodes, the first effect is predominent, hence, the disruptive voltage (per unit of distance) increases with falling pressure, or with decreasing distance between electrodes as the molecules to be ionized become fewer. At high pressures, or with large distances between electrodes, on the other hand, the impeding effect of the molecules is predominant, hence, the disruptive voltage increases nearly in proportion to the pressure and the distance between electrodes.

From this, it is evident that the disruptive voltage is a function of the product of the distance between electrodes and the density of the gas. It has been found to have a minimum value between 300 and 400 v. occurring at a pressure of 1 mm. of mercury for 10 cm. between electrodes.[4]

At extremely close distances between terminals, the breakdown voltage may be very high. Ordinarily, in air at ordinary pressures and distances of a centimeter or more, the breakdown voltage is about 30,000 v. per in. At extremely close distances, the breakdown potential may be 1,000,000 v. The reason for this lies in the fact that when the distance between terminals is very small, the distance through which the ions in the gas can move under the action of the field is too small to enable them to gather sufficient velocity to ionize other atoms by collision. As a consequence, with distances of this order, only under the most extreme potential gradients, (1,000,000 v. per inch or more) can the ions accelerate rapidly enough to gain the velocity required to effect ionization by collision.

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[4] L. A. Hazeltine, Electrical Engineering, p. 283.

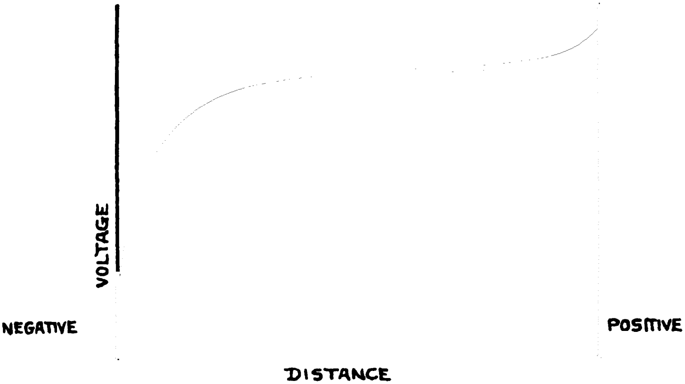

FIG. 119. POTENTIAL GRADIENT ACROSS A STRONGLY IONIZED GAS SPACE

NOTE: Practically all of the voltage becomes concentrated on the space charge.

SPACE CHARGE

In our previous discussion of the vacuum tube, we referred to the phenomenon of space charge. In the formation of an arc or disruptive discharge, the effect space charge is also made manifest.

Suppose we consider the effect of an electric field upon an ionized gas. Negative ions move toward the positive terminal or anode while positive ions move toward the negative terminal or cathode. In the center of the space between terminals, electrons move out toward the anode on one side but as many enter it on the other; therefore the number of electrons in that region remains practically constant. The same is true of the positive ions—as many move out toward the cathode as move in from the other side, hence the total number remains the same.

Close to the terminals, a different action takes place, however. In the space very close to the cathode, for instance, electrons move out toward the positive terminal but no electrons can move into it from the cold cathode. Thus, since electrons are going out and none coming in, this space will be left with a deficiency of electrons and an excess of positive ions, causing this space (close to the cathode) to assume a positive charge.

In the space close to the anode, a similar action takes place. Here positive ions are moving out but none are entering it from the anode, hence this region becomes negatively charged. Thus, we have a positive space charge at the cathode and a negative space charge at the anode.

Now, what is the effect of these space charges? The effect is the same as that of the space charge in a vacuum tube—it results in a distortion of the electric field. Ordinarily, with the space charges, the potential gradient would be uniform and would take the form of a straight sloping line as shown in Fig. 118. In the presence of the space charges, however, many of the lines of force which leave one of the terminals do not reach the other side. They terminate on the space charge. Therefore, we shall have a greater number of lines of force at the cathode or anode than we have in the center; hence, the field may be considerably stronger at the cathode or anode than it is farther out in the gas space. The voltage tends to concentrate next to the electrodes.

From this, it will be evident that the voltage across an arc or an extremely ionized gas space is divided up into three parts: the cathode drop, the anode drop and the drop in the central portion of the arc space. These facts regarding the arc and the disruptive discharge, while interesting enough from a purely academic standpoint, play an important part in all arc phenomena and it is necessary to understand them if we are to have a clear conception of what really happens in the electric arc.

CHAPTER XXIV

THEORIES OF THE ELECTRIC ARC

HAVING AN IDEA OF how a thing acts and actually understanding it are two different things. Often, we think we understand a certain phenomenon, yet when pressed for a detailed explanation, to our own surprise we find that we know very little about it.

So it has been with the theory of the electric arc. It was known for a long time that arc phenomena were due to the presence of electrons in the arc space but when it became necessary to explain just how these free electrons were produced, electric arc phenomena were not quite so simple as they were thought to be.

As long as the current density in the arc was low or when the discharge took place as a glow or brush, the electrons could be accounted for simply on the basis of ionization by collision as explained in the preceding article. But the true arc, the arc we are familiar with in ordinary electrical work, presents features which are quite different from those exhibited in the glow or even in the disruptive discharge. The principal characteristic of the arc is its high current density which means, of course, a high electron density.

It is this high electron density that has been the stumbling block. Calculations show that electron densities in actual arcs come out entirely too high, to be able to account for them purely on the theory of ionization by collision. Certain arcs have been observed in which the current density at the cathode was as much as 30,000 amp. per sq. cm. The voltage gradient in arcs of this kind is usually very low and calculations show that under such low gradients electrons could not gain sufficient velocity to ionize sufficient atoms to produce such high electron densities. Then, where do they come from?

Many have investigated this question and various theories have been proposed but none have been positively accepted as being correct. In this country, Professor K. T. Compton has done a great deal of excellent work on the arc and his theories have been more generally accepted perhaps than those of any other single investigator.

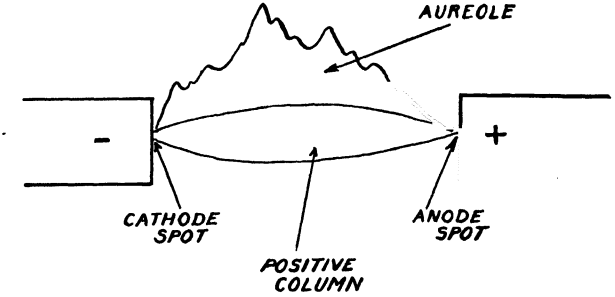

FIG. 120. THE PHYSICAL STRUCTURE OF THE ELECTRIC ARC

The arc consists of four parts as shown. The flame-like portion extending upward from the positive column is due to combustion.

Before we discuss the various theories of the arc that have been proposed it will be well to consider an actual arc to learn something of its physical structure.

STRUCTURE OF THE ELECTRIC ARC

For purposes of study, an electric arc may be considered as being made up of four parts as depicted in the diagram, Fig. 120. By looking at an arc through a blue or dark glass, it will be seen that the arc issues from a bright spot in the cathode and terminates on another bright spot on the anode. These may be called the cathode and anode spots respectively. The central portion of the arc is quite clearly defined—it extends from electrode to electrode in the form of an intensely bright core, which has come to be known as the positive column. Finally, there is seen an outer part of the arc which is a sort of a flame rising upward. According to Dr. Slepian, the Germans call this flame the aureole.

This aureole, from all investigations, seems to be nothing more than a flame due to the combustion of vapors in the arc, for if steps are taken to exclude all oxygen, the aureole disappears. While the aureole is the result of the heat of the arc, rather than a fundamental factor in its formation, it plays an important part in maintaining the arc, once it has been formed, particularly in the case of an alternating current arc. In the alternating current arc, where the potential across the arc passes through zero a number of times per second, there is a tendency for the arc to be deionized at the time of zero potential and if it were not for the

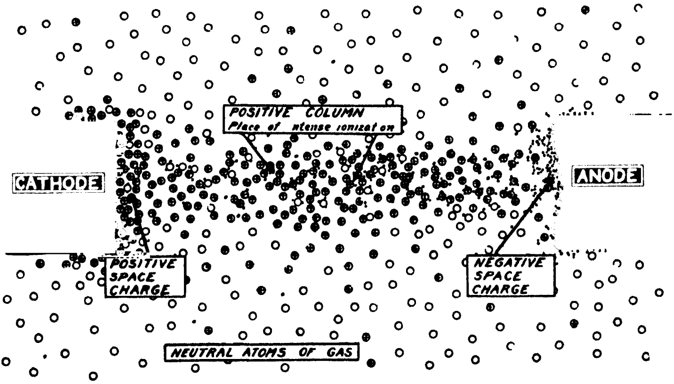

FIG 121 DIAGRAM SHOWING THE CONDITIONS IN A HEAVY DIRECT-CURRENT ELECTRIC ARC

This diagram is necessarily very crude but it attempts to show the manner in which the space charges are located.

presence of the burning gases in the aureole, the arc might fail to restrike when the potential rose again. Where the aureole is present, however, this does not occur, because the chemical combinations of the combustible gases with the oxygen molecules is much slower than the processes of ionization and deionization and as long as these gases keep burning, they provide a source of ionization, which serves to reignite the arc after the voltage has passed through zero and built up again. This reignition of the arc after each passage through zero is responsible for the fabric appearance of a long high voltage alternating current arc when shown on a photograph.

Thus, while the aureole is important in maintaining the arc after it has once formed, it may be considered as a result rather than a cause, and for this reason we need not give it further consideration here.

CONDITIONS AT THE CATHODE

Perhaps the most baffling problem regarding the arc is the explanation of the high current density occurring at the cathode spot. Where do the electrons which make up this current come from?

The cathode, we have seen, is surrounded by a space charge of positive ions but these ions are insufficient in number to account for the high current densities at the cathode observed in practice. This positive space charge, it will be recalled, was created when the potential was first applied and the electrons moved away toward the anode. The positive ions tend to move toward the cathode but being a thousand times more massive than the electrons, they move with only a thousandth part of the speed of the electrons; hence their effect in conducting the arc current is small.

The explanation of the action at the cathode spot, therefore, must be explained in terms of electrons and all lines of evidence indicate that these electrons are in some way emitted from the cathode itself.

To produce such emission, only two processes seem capable of supplying an electron emission from the cathode in sufficient amount; first, thermionic emission, due to the heating of the cathode and, second, the actual pulling of electrons from the cathode by the electric field, or a combination of both. J. J. Thomson and Stark first suggested the former theory and Irving Langmuir the latter one.

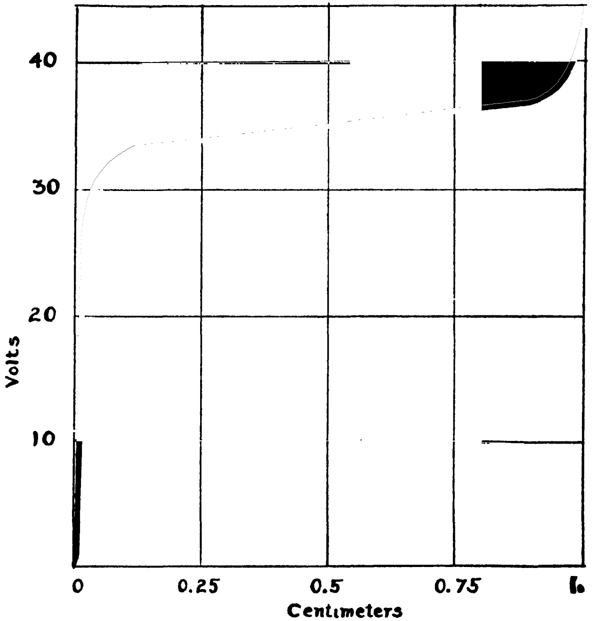

FIG. 122. POTENTIAL GRADIENT CURVE ACROSS AN ARC
Because of the positive space charge at the cathode practically all of the potential drop is adjacent to the cathode.

Offhand, the thermionic emission theory is logical for the temperature of the cathode spot in most cases is high enough for thermionic emission; in fact, actual measurements of the temperatures of a number of different arcs indicate that such thermionic emission actually occurs, particularly where electrodes having high melting points are used. The measurement of the temperature of the cathode spot is a difficult matter, owing to its small size and its frequent rapid motion, yet it has been done with varying success. In the case

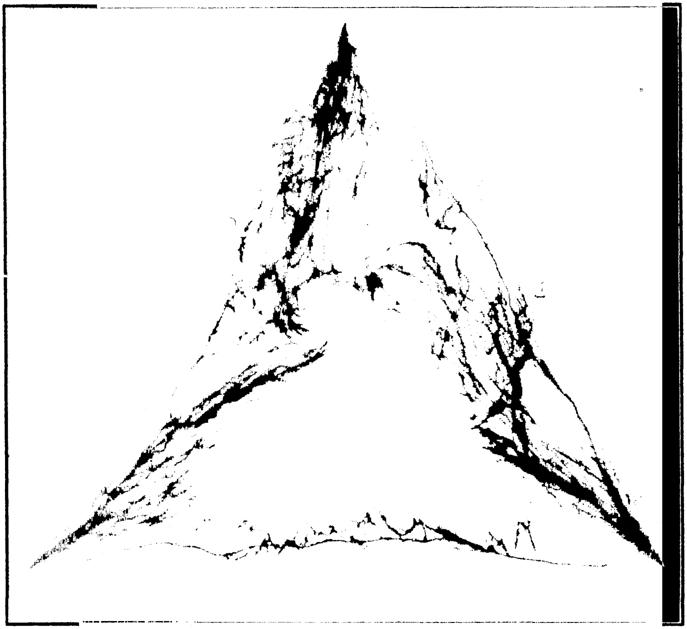

FIG 123 A HIGH VOLTAGE ALTERNATING CURRENT ARC

This is a 3-phase arc, nine feet between points at 1,000,000 v. An arc of this type because of the alternating potential tends to extinguish each time the voltage passes through zero. Because of the high temperature of the surrounding gases, the gases in the path of the arc remain ionized which permits the arc to be restruck as the voltage builds up The arc is restruck along the path which still remains ionized. Due to air currents this path is in slow lateral motion, which results in the fabric like pattern noted in the above photograph The effect is difficult to note on the halftone of carbon or tungsten arcs, the temperatures found checked very well with the current densities for arcs between these materials. With metals of lower melting point, however, where the temperature of the cathode spot is only slightly over the boiling point, the thermionic emission theory does not hold so well, for even when such metals reach the boiling point, the temperature is still too low for intense thermionic emission.

LANGMUIR'S THEORY

In such cases, the theory advanced by Langmuir seems to offer a way out of the difficulty. According to this theory, the electrons are actually pulled out of the metallic cathode by the electric field. Naturally, this could only be done if the field was exceedingly intense but Langmuir has shown that, as the result of the large space charge at the cathode, the field there actually reaches an enormous intensity—in excess of a million volts per centimeter. Under such fields, electrons would be drawn out of the cold metal.

That such a pulling out of electrons from the metal constituting the cathode actually occurs is borne out by certain experiments by Stoltz in Germany and by Dr. Slepian in this country. In these experiments, by means of a magnetic field, an arc was caused to move around on a metal ring so rapidly that so far as observation was concerned the cathode remained practically cold. Dr. Slepian[1] caused an arc of 20,000 amp. to move on a copper surface with great speed, and upon examining the face of the electrode found a little oxidation but no burning or melting whatsoever. These experiments seem to eliminate the necessity for thermionic emission.

While it is probable that in this case there was no thermionic emission, on the other hand, as Prof. Comp-

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[1] Theory of the Electric Arc. Journal of the Western Soc. of Eng. April, 1928.

FIG 124. THE ELECTRIC ARC IS THE HOTTEST PLACE WE KNOW OF ON EARTH

This 2500-amp, 100 v. arc between 4-in. graphite electrodes in a brass melting furnace attains a temperature of within 40 per cent of that in the sun.

ton has pointed out, there are many cases where melting and fusing of the electrodes does occur and in such cases it is certain that thermionic emission occurs with marked effect. In such cases, also, it is probable that the emission of electrons from the cathodes is aided by the pulling-out effect of the electric field, that is, the emission current is due to a combination of both causes.

While it may seem unreasonable at first thought to assume that a potential gradient high enough to pull electrons out of the cold metal could exist at the cathode, it can be easily demonstrated mathematically[2] that such an intense field may exist. This high potential gradient is due, directly to the positive space charge surrounding the cathode.

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[2] K. T. Compton, The Electric Arc. A.I.E.E. Transactions, 1927.

In the preceding article it was shown that a large portion of the total voltage drop existing across a highly ionized gas space is concentrated in the space immediately adjacent to the cathode. There is, of course, also a space charge at the anode and this is usually negative (although it may be positive) but its value is considerably less than that of the positive space charge due to the greater mobility of the electrons. The positive ions are ponderous, compared to the electrons and their speed (toward the cathode) is only a thousandth part of that of the negative ions or electrons. For this reason, their power of ionizing atoms near the cathode is almost negligible and, as a consequence, the space immediately adjacent to the cathode contains a great excess of positive ions. Since this layer (if we may call it so) of positive ions is located extremely close to the cathode, it is evident that an extremely intense field of force will be set up between the cathode and the positive space charge. From our study of the electric field[3] we know that the force varies inversely as the square of the distance between charges, hence, if, as in this case, the distance between charges is of the order of molecular spacing, the potential gradient may attain values of millions of volts per centimeter. Such gradients would suffice actually to pull electrons out of cold metal electrodes in such quantities as to be able to account for the high electron densities found in the electric arc.

Thus it is probable, in most cases, that the current at the cathode is due to two actions, thermionic emission and the pulling out effect of the field, although neither of these theories has been definitely proved. The thermionic theory alone, while it may suffice in some cases to account for the arc current, in other instances falls down.

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[3] Page 56.

One other theory has been proposed, this by Dr. Slepian.[4] In this he assumes that the current is carried not by electrons coming from the cathode but by positive ions coming from the highly ionized gas next to the cathode. Because of the extremely high energy concentration, a thin layer of gas next to the cathode, it is possible, is raised to a very high temperature—up to 10,000 deg. C. At this temperature, the thermal ionization of the gas would be almost complete. With such a high degree of ionization, it can be demonstrated mathematically that the positive ions are able to carry the required current density.

One word about thermal ionization; this is really a special case of ionization by collision. We have seen that as the temperature of a body, particularly a gas, is raised the molecules and atoms are invested with a greater amount of kinetic energy and as a consequence move about more energetically. The free electrons in such a body, under these conditions, also acquire more energy and as their velocity increases, the impacts of their collisions with atoms become more violent. It can be imagined that if the temperature of the body is raised high enough, the free electrons will acquire speed enough to begin to ionize by collision. Thus, this type of ionization, which can occur only at extremely high temperatures, is known as thermal ionization.

This is about as much as is known today about the conditions at the cathode of the electric arc. Conditions in the other parts of the arc, at the positive column and at the anode are more easily accounted for.

CONDITIONS IN THE POSITIVE COLUMN

In the positive column, a combination of actions probably takes place. The positive column is characterized by high conductivity for in heavy direct-current arcs the current density may be many thousands of amperes per sq. cm. while the voltage gradient may be as low as 20 v. per in. This part of the arc, therefore, is the seat of intense ionization.

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[4] In discussion of K. T. Compton's paper, The Electric Arc. A.I.E.E. Proceedings, 1927. P. 879.

At first thought, it might appear as though this ionization might be due to collision but with a voltage gradient of only 20 v. per in., such intense ionization as is actually observed would be impossible. Compton suggests that much of it is thermal ionization and while this is true no doubt in the case of high temperature arcs such as the carbon or tungsten arc thermal ionization certainly plays no role in maintaining the mercury arc. Other factors exist, however, such as ultra violet radiation and since the arc is the seat of intense ultra violet radiation, this may be responsible for a large part of the ionization in the positive column, particularly in the mercury arc. It is quite evident, however, that there is no one cause of the ionization; it is the result of a combination of causes.

We have now considered the conditions at three parts of the arc, first, in the aureole, second, at the cathode and third, in the positive column. Only those at the anode remain to be discussed.

The current at the anode is due to the negative space charge set up near the anode when the positive ions move away toward the cathode. A high potential gradient is thus established, resulting in a steady movement of electrons toward the anode. This movement of electrons to the anode is more than sufficient to account for the high current densities found in heavy current arcs.

Since the arc is the seat of violent interchange of energy between atomic systems, it is naturally characterized by a rise in temperature; in fact, in the arc, we have the highest temperature found on earth.

Ever since the carbon arc was first used as an illuminant, it was known that practically all of the light was emitted from the incandescent crater of the positive electrode, that is, the anode. This fact is significant when the conditions at the anode discussed above are considered. The extremely high temperature found at the anode is due to the thousands of billions of high speed electrons impinging on the anode. Each electron is endowed with a certain amount of kinetic energy and as it strikes the anode, this kinetic energy is released and appears as heat and light.

This brings to a close our purely analytical study of the mechanism of the electric arc. In spite of its apparent simplicity, it will be evident that the arc is an extremely complex electrical phenomenon and one not easily understood. There are many other interesting facts about the arc and its application which can be explained on the basis of the electron theory and some of these will be considered.

CHAPTER XXV

CONCLUDING CONSIDERATIONS OF THE ELECTRIC ARC

THUS FAR, OUR discussion of the electric arc has been confined almost entirely to the type of arc exemplified by the sustained discharge between two electrodes brought about by the disruption of the insulating gas due to the application of high voltage. While many arcs encountered in electrical work are started in this manner, the large majority of arcs with which the electrical engineer and electrician is concerned are those started when two electrical contacts are separated. This is the type of arc formed at the contacts of a switch or circuit breaker when it is opened. The difference between an arc formed at the contacts of a switch and that produced between separated electrodes by high potential is only in the manner in which the arc is started. Once formed, both types of arcs have the same characteristics.

There is also another type of arc with which almost everybody is familiar but which is not recognized as such and that is the type of arc exemplified by the mercury vapor lamp and the neon tube electric sign. While these arcs present characteristics quite different from the heavy current arc at atmospheric pressure, they are classified as arcs since they are examples of true gaseous conduction. The temperatures attained in this type of arc are considerably lower than those of the heavy current arc.

The neon and the mercury arcs are low pressure arcs, that is, the gas in which the discharge occurs is at a pressure below that of the atmosphere. In the mercury arc, the conduction is between a metal electrode and the surface of a small bright cathode spot on the surface of a pool of mercury in a glass tube exhausted to a pressure of from 0.05 to 1 mm. The mercury is always the cathode. When in operation, the cathode spot dances around continually and is evidently at a high temperature. In principle, however, the mercury arc is not greatly different from the types already described. The same element of doubt exists as to the actual reason for the intense electron emission at the cathode, but it is believed to be due largely to the "pulling out" effect of the positive space charge. So much for the mercury arc.

WHAT OCCURS WHEN TWO CONTACTS ARE SEPARATED

Now, let us consider what occurs when an arc is formed by separating two metallic contacts carrying current. It is common knowledge that when an electric circuit is suddenly interrupted by the opening of a switch or the breaking of a conductor, a bright spark appears at the instant of the break. This spark appears even when the currents and voltages involved are quite small. If a circuit containing only a single dry cell is broken a spark of this type is produced, yet the voltage is only 1½ v. or less.

From our previous study of arc phenomena, we learned that certain minimum voltages are required to start an arc—several hundred in most instances. Why is it, then, that the opening of a circuit under potentials as low as 1 or 1½ v. gives rise to such brilliant sparks? Despite the low voltages and small currents used, the breaking of these circuits evidently produces high temperatures.

Consider two copper rods placed in contact end to end, as shown in Fig. 125, so that an electric current may flow from one to the other across the joint. Now, by means of a millivoltmeter, suppose we measure the resistance of a few inches of this circuit at two places, as

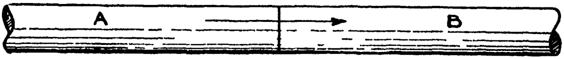

FIG 125. TWO CONDUCTORS A, AND B, PLACED END TO END

shown in Fig. 126, first at R and second, across the joint J. Unless the rods have been joined by welding or brazing, it will be found that the resistance at the joint will be slightly higher than that of the copper rod itself. What is the reason for this?

The reason is simple and will be evident at once if we examine the joint carefully by means of a magnifying glass or under a microscope. Looking at it through a magnifying glass, we shall find that the apparently smooth parallel surfaces of the ends of the rod are quite rough and if we apply a high powered microscope, it will be found that the surfaces are not smooth at all and that the rods only make contact at a few places. If pressure is applied to the ends of the rods, the resistance of the joint will decrease and observation by

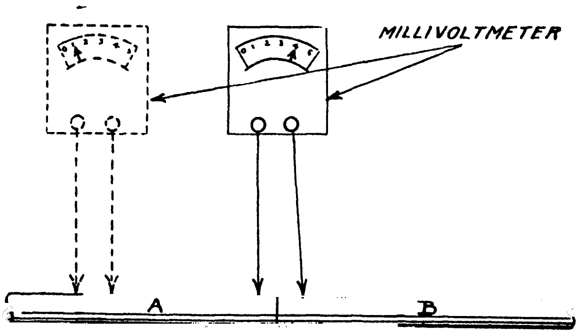

FIG. 126. MEASURING THE VOLTAGE DROP ALONG TWO PORTIONS OF THE JOINED CONDUCTOR, FIRST ALONG A PORTION OF THE SOLID CONDUCTOR AND THEN ACROSS THE JOINT. THE DROP ACROSS THE JOINT IS GREATER BECAUSE OF THE GREATER RESISTANCE

means of the microscope will show that due to the compression, many of the points of contact have increased in area and in addition others have been established. It is evident, therefore, that under the latter condition since there are more paths across the joint for the current to travel, the resistance to the total current will be decreased.

As a matter of fact, although we think of the two ends of the rod as being in actual contact, from our study of atomic structure we know that the atoms of the two rods are never in actual contact. Even at the points of contact referred to above, the spacing between two atoms of rods A and B, respectively can never be less than the spacing between the atoms in the rods proper. Thus, at C in Fig. 130, two atoms A′ and B′ of the rods A and B, respectively, are probably as close together as they will ever be, regardless of how much force is used to press the rods together. When more pressure is applied, instead of the atoms A′ and B′ approaching each other more closely, the spaces S_1, S_2, etc., will tend to fill up. Finally, if enough pressure is applied and provided no atoms of gas or oxide are entrapped between the atoms of copper, all the atoms at the ends of the two rods would be as close together as are the atoms in the rods themselves, and the rods would become *one*.

This, of course, is actually what occurs when two rods are welded together. In this case the rods are first heated so that the distance between the atoms is increased, thus permitting them to slide over each other, so to speak, with greater ease.

Having analyzed the action which takes place when two rods are pressed together, it is a simple matter to imagine the sequence of events which obtains when the process is reversed, that is, when two rods are pulled apart to break an electric circuit.

As the pressure is released and as the force on the rods is reversed, there is a gradual separation of the atoms at the boundaries. First, those points which have been under the least stress open up and as the compressive stress is still further decreased other points open up. Finally, (although all of this may occur in the ten thousandth part of a second) there comes a time when the actual contact area of the rods is reduced to a geometric point—the last point of contact.

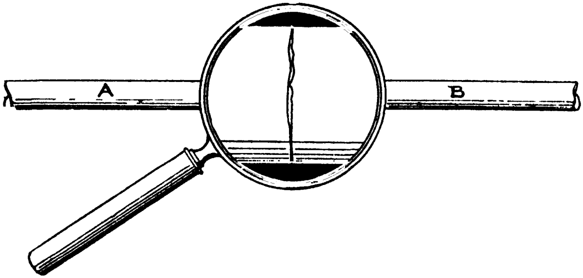

FIG. 127. LOOKING AT THE JOINT THROUGH A MAGNIFYING GLASS

The joint, it will be noted, is not perfectly smooth and contact is made only at certain points.

RESISTANCE OF THE LAST CONTACT

Now it is evident, that as this occurs—as the contact area of the rods is reduced more and more, the resistance across the joint becomes larger and larger. When the contact area finally reduces to a geometric point, this resistance becomes infinite.

Thus, it is evident that if a gaseous discharge has not started before, all the voltage of the circuit will finally concentrate on this last geometric point. With metal electrodes, this means that there will be an enormous concentration of current and power at the last contact so that an extremely high temperature will be obtained. This temperature, even though only a single volt is acting, comes out far greater than that necessary to melt or even vaporize the metal of the contacts.

Dr. Slepian[1] has investigated this matter and has derived an equation which gives the temperature rise of a small contact between large electrodes under an applied voltage. This is

$$T = \frac{E^2}{33.5\ kp}$$

when E is the applied voltage, p the electrical resistivity in ohms per cubic cm., k, the thermal conductivity in calories per sq. cm. per deg. C. per cm., and T the temperature in degrees C.

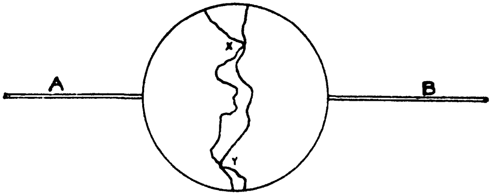

FIG. 128. UNDER A HIGH POWERED MICROSCOPE, THE JOINT WOULD LOOK SOMETHING LIKE THIS

Here the roughness of the surfaces is shown even more clearly. In this section, contact is made only at the points X and Y.

Applying this equation to the case of a metal having values $p = 10^{-5}$ and $k = 1.0$, for a difference of potential of one volt we find that the temperature produced at the last contact is

$$T = \frac{1}{33.5 \times 1.0 \times 10^{-5}} = 3000 \text{ deg. C.}$$

If, instead of one volt, the potential acting on the circuit is 10 v., the temperature comes out theoretically at least, 300,000 deg. and with 100 v., 30,000,000 deg. Of course such temperatures as the last two are never reached and perhaps neither is the first, but this equation shows that temperatures sufficiently high to vaporize the metal of which the contacts are made may be obtained even with very small voltages. With such high temperatures also, there should be sufficient thermionic emission to start ionization of the gases between the contacts, thus establishing an arc.

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[1] Temperature of a Contact. Journal of the A. I. E. E., Oct. 1926, p. 930.

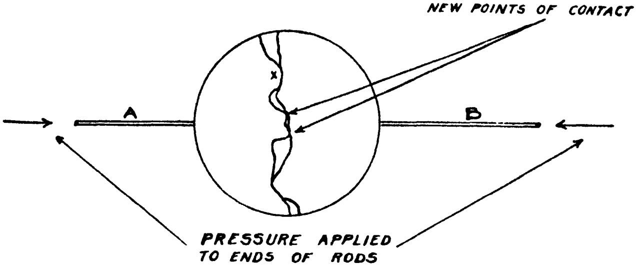

FIG. 129. A MICROSCOPIC VIEW OF THE SAME SECTION AS THAT SHOWN IN FIG. 128 WHEN PRESSURE IS APPLIED TO THE ENDS OF THE RODS

Upon the application of pressure, the points of contact X and Y are broken down and the area of contact increased. This allows other portions of the rods to approach each other more closely, thus establishing new points of contact. Thus the application of pressure decreases the resistance of the joint.

EFFECT OF GAS ON THE ARC

Although an arc can be started in this manner, the continuance of the arc after the contacts have separated must be due to some process of ionization of the gases between the arc terminals. This is borne out by certain experiments by Sorensen and Mendenhall[2] on breaking electric circuits in vacuum.

If the arc is actually due to ionization of gases between the terminals, it is evident that in a perfect vacuum an arc could not be maintained. Of course, by introducing a heated cathode into a vacuum as is done in a vacuum tube, a space current will flow but this is not an arc in the usual sense. A number of investigators, before Sorensen and Mendenhall had experi-

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[2] Vacuum Switching Experiments. A. I. E. E. Transactions, 1926, page 1102.

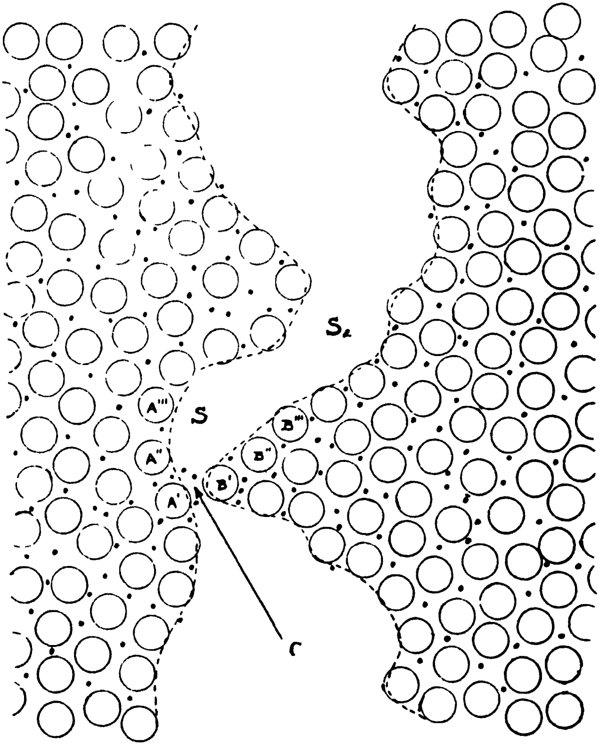

FIG. 130. IF WE COULD ACTUALLY SEE ATOMS, THIS IS HOW THE JOINT WOULD APPEAR

The point C is what we call a point of contact, but as will be noted there is no actual contact of the atoms A′ and B′. These two atoms are probably as close as they ever will be, the distance between them being the same as the distance between the atoms of the metal. If pressure is applied, the atoms A″, A‴ and B″, B‴ will undergo displacement, causing the space S, to diminish.

mented with switching in vacuum, without very definite results. Even in high vacuum (0.001 mm.) they found severe burning of the contacts and luminous flashes, at the instant of opening with currents of one and two amperes.

The failure of these experiments in suppressing the formation of an arc was due, evidently, to the fact that the degree of vacuums used[3] was insufficient. Sorensen not only used the best obtainable exhausting equipment, but all the electrodes used were carefully denuded of all gases. The vacuums used were as high as 10^{-6} mm.

With such vacuums, Sorensen found that even when the switch opened 926 amp. at 41,500 v. there was no pitting or burning of the contacts and no appreciable arc. When the contacts separated, there was a visible arc, but this persisted for only a very small fraction of a second. This flash no doubt was due to the heating of the last contact point and the consequent thermionic emission, but because of the absence of gas in the vicinity this thermionic emission did not produce ionization.

From these experiments, it is very evident that arc is dependent upon the presence of gas, and that the arc is largely an ionization phenomenon, in which the electron plays a most active part.

Before leaving this subject of the electric arc, it may be of interest to investigate briefly, why an arc can be maintained more easily in certain gases than in others. This is due to the difference in ionization potentials of different gases.

Ionization has been described as the process of removing an electron from a neutral atom against the attractive power of the nucleus of the atom. Now, it may be recalled from our consideration of the structure of atoms of various chemical elements, that certain of the electrons in the outer orbits were more easily removed than others; in fact, it was the varying tendency of atoms to lose or acquire electrons that was responsible for the ability of one chemical element to combine with another. Certain elements were found to have atoms in which the electrons were so disposed as to form exceedingly stable systems—these were the inert gases, helium, neon, argon, krypton, etc. There were other elements, such as sodium and lithium which had a single electron in one of the outer orbits which was easily removed. Thus the atom of helium with two electrons in its orbit is stable and neither of the electrons is easily removed, but the atom of lithium with three electrons, one in the outer orbit, is unstable with its third electron and for this reason is willing to give up this third electron.

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[3] As high as 0.001 mm.

An atom of this latter type, it must be obvious, can be ionized more easily than can one of the former type and this is borne out by experiment. The ionization potential of helium, for instance, is about 25 volts, while that of lithium is 5.1 volts. In other words, a free electron must fall through 25 volts before it acquires sufficient velocity to ionize a neutral atom of helium but in the case of lithium, it need fall through only 5.1 v. Thus certain gases have lower ionizing potential than others and therefore are better suited to maintain the electric arc.

End of Vol. I

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